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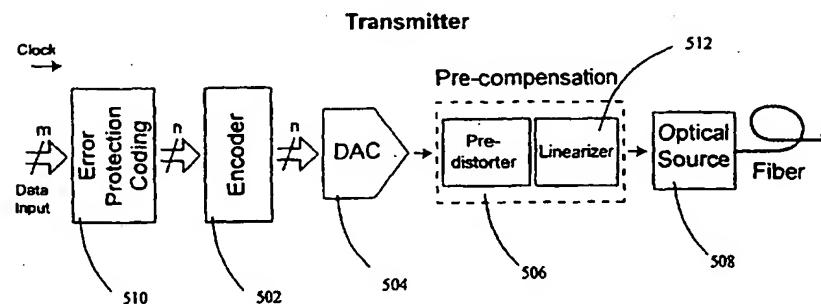
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(57) Abstract: Data throughput rates are increased in an optical communication system (500) without requiring replacement of the existing optical fiber in a link. Channel throughput is increased by upgrading the components and circuitry in the head and terminal of an optical communication system link (500). The increase in system throughput is achieved by using advanced modulation techniques (502) to encode greater amounts of data into the transmitted spectrum of a channel, thereby increasing the spectral efficiency of each channel. This novel method of increasing transmission capacity by upgrading the head and terminal of the system to achieve greater spectral efficiency and hence throughput, alleviates the need to replace existing fiber plants. Spectrally efficient complex modulation techniques (502) can be supported by interface circuits with an increased level of signal processing capability in order to both encode multiple bits into a transmitted symbol and decode the original data from the received symbol.



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## INCREASING DATA THROUGHPUT IN OPTICAL FIBER TRANSMISSION SYSTEMS

### PRIORITY AND RELATED APPLICATIONS

The present application claims priority to provisional patent application 10 entitled, "Multi-level Logic for Optical Transceivers," filed on December 21, 2000 and assigned U.S. Application Serial No. 60/257,598. The present application also claims priority to provisional patent application entitled, "Advanced Signal Encoding/Decoding Techniques for Equalization of Multilevel Optical Communication Signals," filed on December 21, 2000 and assigned U.S. Application 15 Serial No. 60/257,596. The present application also claims priority to provisional patent application entitled, "Method for Mode Separation Imaging and Detection of the Distinct Spatial Modes of a Multimode Optical Fiber or Multimode Optical Cavity," filed on December 24, 2000 and assigned U.S. Application Serial No. 60/257,586. The present application also claims priority to provisional patent 20 application entitled, "Higher Order Modulation Techniques for Optical Transceivers," filed on December 21, 2000 and assigned U.S. Application Serial No. 60/257,551. The present application also claims priority to provisional patent application entitled, "Method of QAM Generation and Demodulation Techniques," filed on April 19, 2001 and assigned U.S. Application Serial No. 60/284,457. The present application also 25 claims priority to provisional patent application entitled, "Mixed Signal Processing for Distortion Compensation of Multilevel Optical Communication Signals," filed on March 29, 2001 and assigned U.S. Application Serial No. 60/279,916. The present application also claims priority to provisional patent application entitled, "Automatic Threshold Tracking and Digitization Method for Multilevel Signals," filed on April 4, 30 2001 and assigned U.S. Application Serial No. 60/281,526. The present application also claims priority to provisional patent application entitled, "Parallel Noise Filtering for Multi-Level Optical Data Reception," filed on April 24, 2001 and assigned U.S. Application Serial No. 60/286,070. The present application also claims priority to 35 provisional patent application entitled, "Adaptive Equalizer for Multi-Level Optical Data Receiver," filed on April 19, 2001 and assigned U.S. Application Serial No. 60/284,949. The present application also claims priority to provisional patent application entitled, "Linearization of Optical Modulation," filed on April 19, 2001

5 and assigned U.S. Application Serial No. 60/284,964. The present application also claims priority to provisional patent application entitled, "System and Method for Increasing Throughput in Optical Fiber Transmission Systems," filed on July 11, 2001 and assigned U.S. Application Serial No. 60/304,718. The present application also claims priority to provisional patent application entitled, "High-Speed Multilevel  
10 Light Modulator Driver Circuit," filed on May 9, 2001 and assigned U.S. Application Serial No. 60/289,674.

## FIELD OF THE INVENTION

The present invention relates to optical fiber communication systems and more particularly relates to increasing the throughput of data transmission over an optical  
15 fiber communication system through the use of multilevel modulation.

## BACKGROUND OF THE INVENTION

In virtually all fields of communications, there exists a persistent demand to transmit more data in less time. The amount of information that can be transmitted over a communications system (or through a component of that system) is referred to  
20 as the bit rate or the data throughput of the system. Traditionally, system throughput is increased by either increasing the number of channels carrying information or increasing the bit rate of each channel. In order to meet ever-increasing bandwidth demands, aggregate throughput in fiber optic transmission systems has conventionally been increased by using multiple Wavelength Division Multiplexed (WDM) channels,  
25 time-division-multiplexing (TDM), or some combination of the two techniques. WDM techniques increase the number of channels transmitted on a particular fiber, while TDM techniques increase the data rate of each individual channel.

Conventional optical fiber networks typically can deliver on the order of 10 Gigabits of data per second (10 Gb/s). Both WDM and TDM techniques have been applied to realize fiber channel bit rates well above this conventional 10 Gb/s capacity. Many fiber optic communication systems comprise multiple WDM channels simultaneously transmitted through a single optical fiber. Each of these channels operates independently at a given bit rate,  $B$ . Thus for an  $m$  channel WDM system, the system throughput is equal to  $m \cdot B$ . Conventional dense WDM (DWDM) systems typically operate with 40 to 100 channels. There are certain restrictions, however, that limit the aggregate power that can be transmitted through a single

5 DWDM optical fiber (i.e., the launch power). For example, eye safety power regulations and nonlinear effects in the fiber place limits on the aggregate launch power. In addition, channel spacing limitations and per-channel launch power, effectively limit the number of WDM channels that can be combined for transmission on a single fiber.

10 TDM techniques also are associated with various limitations. For example, using conventional TDM techniques to achieve an  $n$ -times increase in channel data rates requires the optical components of a link (e.g., the modulator and photodetector) to be replaced with new optical components having  $n$ -times the bandwidth of the original optical components. In addition, the interface circuitry must be replaced with  
15 new circuitry having bandwidth  $n$ -times greater than the original circuits.

Optical fiber networks are typically comprised of a series of links that include a transmission block, a receiver block, and a long stretch of optical fiber connecting the two blocks (i.e., the optical plant). Figure 1 is a block diagram of a conventional  $m$ -channel WDM fiber optic transmission system link 100. The fiber optic  
20 transmission system link 100 consists of a WDM transmission block 102 (denoted as the "Head"), the optical fiber 104, and a WDM reception block 106 (denoted as the "Terminal"). The Head 102 comprises  $m$  transmitters 108-112 (labeled "Tx") and an  $m$ -channel WDM multiplexer 114. Each transmitter 108-112 comprises an optical source (not shown) and all circuitry necessary to modulate the source with the  
25 incoming data stream. For the case of external modulation, the transmitter block also includes a modulator. The Terminal 106 comprises an  $m$ -channel WDM demultiplexer 116 and  $m$  receivers 118-122 (labeled "Rx"). Each receiver 118-122 comprises a photodetector (not shown) and all circuitry required to operate the detector and amplify the detected signal in order to output the original electrical data  
30 stream.

In order to realize channel data rates of 10 Gb/s and beyond, the optical fiber 104 as well as the Head 102 and Terminal 106 of the link 100 are typically upgraded to support the increased data rates. In order to increase the channel bit rates in this conventional link 100, each transmission block 102 and reception block 106 must be  
35 replaced with optical components and circuitry capable of achieving the desired bandwidths. For high-speed channel bit rates (10 Gb/s and faster), the optical fiber 104 also must often be replaced in order to compensate for signal distortions, which

5 are more prominent at higher data rates. This process can be particularly cumbersome and costly in a long-haul link where hundreds of kilometers of fiber must be replaced. For existing long-haul optical links, the complexity and cost of replacing planted fiber often represents a prohibitive barrier for increasing channel bit rates.

10 Service providers seeking to optimize revenue and contain cost prefer a highly granular, incremental expansion capability that is cost effective while retaining network scalability. The ability to increase the throughput capacity of single point-to-point links or multi-span links without upgrading or otherwise impacting the remainder of the network is highly desirable from an engineering, administrative and profitability standpoint.

15 In view of the foregoing, there is a need for a method of increasing a channel data rate in a fiber optics communication link that does not require replacing an existing optical fiber plant or necessitate a change in the expensive optical components. There exists a further need to increase the efficiency of the available spectrum within a given fiber optic communication link and to obtain efficient highly granular bandwidth upgrades without upgrades to an existing optical fiber plant, upgrades to channel combing optics, or significant changes to existing maintenance and administrative procedures. The method should further allow service providers to increase data throughput on a per-link basis as throughput demands increase, generating higher profitability for the service provider and lower cost for the consumer.

#### SUMMARY OF THE INVENTION

The present invention increases channel data throughput rates without requiring replacement of the existing optical fiber in a link (i.e., the optical fiber plant). In one aspect of the present invention, channel throughput is increased by upgrading the components and circuitry in the head and terminal of an optical fiber communication system link. Advantageously, the present invention can increase aggregate throughput in fiber optic links beyond the limits of conventional WDM upgrades, while eliminating the necessity of replacing existing fiber plants. In addition to providing an alternative to expensive TDM or WDM upgrades, the proposed invention may also be used in tandem with these approaches to achieve even greater increases in data transmission rates. The increase in system throughput is

5 achieved by using advanced modulation techniques to encode greater amounts of data into the transmitted spectrum of a channel, thereby increasing the spectral efficiency of each channel. Representative modulation techniques include  $2^n$ -ary amplitude shift keying ( $2^n$ -ASK),  $2^n$ -ary frequency shift keying ( $2^n$ -FSK),  $2^n$ -ary phase shift keying ( $2^n$ -PSK), as well as combinations of these techniques such as quadrature amplitude modulation (QAM). Because optical fiber has a finite bandwidth, these types of  
10 spectrally efficient modulation techniques provide a viable solution for extending channel data rates beyond the limits of standard OOK modulation. The spectral efficiency is improved because all  $2^n$ -ary variations occupy essentially the same optical bandwidth. Thus a link employing 16-level ASK modulation can have the  
15 same spectral occupancy as a 2-level OOK link.

The present invention provides a novel method of increasing transmission capacity by upgrading the head and terminal of the system to achieve greater spectral efficiency and hence throughput. The novel method eliminates the need to replace existing fiber plants. The advanced modulation techniques described above add little  
20 or no complexity to the optical components of the channel transmitter and receiver, further reducing the cost of a system upgrade. For  $2^n$ -ary ASK modulation, which uses  $2^n$  different signal levels (amplitudes) to form  $2^n$  different transmission symbols, an  $n$ -times increase in channel throughput can be provided using the same bandwidth, lasers, modulators, and photodetectors as those used in the original on-off-keyed  
25 (OOK) link. Spectrally efficient complex modulation techniques can be supported by interface circuits having an increased level of signal processing capability in order to both encode multiple bits into a transmitted symbol and decode the original data from the received symbols.

The present invention also provides novel signal processing methods that  
30 enhance the transmission of a multilevel optical signal over existing fiber optics communication systems. A novel pre-distortion circuit modifies the transmitted signal based on knowledge of prior data and known link linear and nonlinear performance. A novel linearizer circuit can be used to introduce a nonlinearity into a transmitted signal to precisely counteract any nonlinearities of the optical source.  
35 Additionally, a novel forward error correction process is used to enhance the quality of the decoded multilevel signal.

5        The various aspects of the present invention may be more clearly understood and appreciated from a review of the following detailed description of the disclosed embodiments and by reference to the drawings and claims.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of a conventional  $m$ -channel WDM fiber optic  
10 transmission system.

Figure 2 is a block diagram of an  $m$ -by- $n$ -channel WDM long-haul fiber optic link constructed in accordance with an exemplary embodiment.

Figure 3 is a diagram showing a representation example of a 16-level signal, where each symbol represents four independent bits, with one such representation  
15 shown to the right.

Figure 4 is a graph illustrating the optical power penalty as a function of normalized data rate for a multilevel ASK signal as compared to an equivalent data rate OOK signal.

Figure 5 is a block diagram of an exemplary transmitter.

20        Figure 6 is a block diagram of an alternative exemplary transmitter.

Figure 7 is a circuit diagram of a traditional laser driver.

Figure 8 is a circuit diagram of an exemplary multilevel laser driver.

Figure 9 is a schematic diagram of an exemplary adjustable binary-weighted multi-output current source.

25        Figure 10 is a circuit diagram of an exemplary pre-distortion compensation circuit.

Figure 11 is a diagram illustrating an example of a multilevel data stream.

Figure 12 is an illustration of an exemplary precompensation circuit.

Figures 13 (a) and (b) are diagrams of the typical nonlinearities of (a) Mach-  
30        Zehnder modulators and (b) directly modulated laser diodes.

Figure 14 is a circuit diagram of an exemplary linearization network applied to a directly modulated laser diode.

5       Figure 15 is a circuit diagram of a exemplary linearization network applied to  
a voltage driven optical modulator.

Figure 16 is a schematic diagram of the general structure of a nonlinear  
element (NLE).

10      Figure 17 is an illustration of the current contributions resulting from the two  
types of branch networks making up a nonlinear network.

Figure 18 is a block diagram of an exemplary receiver.

Figure 19 is a block diagram of an exemplary programmable transversal filter  
(PTF).

Figure 20 is a block diagram of an exemplary adaptive equalizer.

15      Figure 21 is a block diagram of an exemplary multi-level parallel noise filter.

Figure 22 is a timing diagram for an exemplary N-channel parallel optimal-  
filter.

Figure 23 is a block diagram of an exemplary N-channel parallel optimal-  
filter.

20      Figures 24 (a) and (b) are an eye-diagram of the simulated data of a 16-level  
transmission and a histogram of the data, which clearly shows the location of the  
“eyes”.

Figure 25 is a block diagram of an exemplary 4-level multi-level receiver.

25      **DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS**

Exemplary embodiments of the present invention enable an increase in  
channel data rates without the replacement of an existing optical fiber plant. Various  
embodiments of the present invention use a novel multilevel modulation technique to  
effect a substantial increase in data rate. Advantageously, various embodiments of the  
30     present invention enable a substantial data throughput increase in a fiber optics  
communication system without requiring a modification of the optical fiber plants  
associated with the system. Specifically, the increase in data rate can be  
accomplished in various embodiments of the present invention by upgrading head and  
terminal components, namely, the system transmitters and receivers. The transmitters

5. and receivers can be modified to include advanced  $2^n$ -ary modulation (demodulation) technology for encoding (decoding) greater amounts of data within the channel spectrum. Representative advanced modulation techniques include multilevel amplitude, frequency and phase shift keying modulations. An exemplary transmitter comprises an  $n$ -channel encoder, a digital-to-analog converter (DAC), pre-compensation circuitry, and an optical source. An exemplary receiver comprises an optical detector, distortion post-compensation circuits, an analog-to-digital converter (ADC), and an  $n$ -channel decoder.
- 10

Figure 2 is a block diagram of an  $m$ -by- $n$  channel WDM optical transmission system 200 comprising a WDM transmission block (denoted as the "head") 202, the optical fiber 204, and a WDM reception block (denoted as the "terminal") 206. The head 202 comprises  $m$   $n$ -channel transmitters (labeled "Tx") 208 and an  $m$ -channel WDM multiplexer 210. Each transmitter 208 comprises an optical source and all circuitry necessary to modulate the source with the incoming data stream. For the case of external modulation, the transmitter block also can include a modulator (not shown). The terminal comprises  $m$   $n$ -channel receivers (labeled "Rx") and an  $m$ -channel WDM demultiplexer. Each receiver typically comprises a photodetector and all circuitry required to operate the detector and to amplify the detected signal in order to output the original electrical data stream.

15

20

In comparison to the prior art optical transmission system illustrated in Figure 1, the system of Figure 2 has been upgraded for increased channel data rates by replacing each transmitter and each receiver of Figure 1 with multi-level modulation technology transmitters and receivers. Representative advanced modulation techniques include  $2^n$ -ASK,  $2^n$ -FSK,  $2^n$ -PSK, and combinations of these techniques (i.e.  $2^n$ -QAM). Significantly, the increase in system throughput achieved by the transmission system of Figure 2 is achieved without replacing the optical fiber network or the interface components connected to the transmitters 208 and to the receivers 212.

25

30

The embodiment presented herein provides a method of generating and receiving light to form a spectrally-efficient high-speed ASK optical link. It will be appreciated by one skilled in the art that an FSK signal can be converted into an ASK signal by using a conventional filter, and similarly a PSK signal can be converted into an ASK signal by using a conventional interferometer. QAM modulation is a

35

5 combination of PSK and ASK and can thus be converted into two ASK data streams. Therefore, the exemplary embodiment addresses the enabling technologies required to process high-speed multilevel signal streams of which ASK is exemplary.

Figure 3 depicts an exemplary multilevel ASK signal 300, combining four bits (i.e., 16 possible amplitude levels) into each single transmitted pulse, or symbol. A  
10 multilevel signal allows for more than one bit to be transmitted per clock cycle, thereby improving the spectral efficiency of the transmitted signal. For multilevel optical transmission, some characteristic (i.e., signal property) of a transmitted pulse (such as amplitude, phase, etc.) is modulated over  $2^n$  levels in order to encode  $n$  bits into the single pulse, thereby improving the spectral efficiency of the transmitted  
15 pulse. Multilevel modulation can increase aggregate channel throughput by combining  $n$  OOK data streams (each with bit rate,  $B$ , in bits/s) into one  $2^n$ - level signal (with a symbol rate,  $B$ , in symbols/s) for an aggregate throughput (in bits/s) that is  $n$  times greater than  $B$ . The aggregate data rate of the signal shown in Figure 3 is four times greater than a corresponding OOK signal with a bit rate equal to the  
20 multilevel symbol rate. As the simplest case, OOK can be regarded as a two level multilevel signal where the symbol rate and bit rate are equal.

As a specific example, the assumption may be made that the 16-level signal in Figure 3 has a symbol rate of 2.5 Gsym/s. That is, a pulse e.g., 302-306 with one of 25 16 possible amplitudes is transmitted at a rate of 2.5 Gigapulses/s. Therefore, the aggregate data rate of the 16-level signal is actually 10 Gb/s ( $4 \times 2.5$  Gb/s) because each pulse (i.e., symbols) can represent a distinct value of four bits. The optical components required to transmit and receive a 16-level 2.5 Gsym/s signal are nearly identical to those required for transmitting and receiving an OOK 2.5 Gb/s signal. The components are at least a factor of two times less costly than the components required for an OOK 10 Gb/s signal. In addition, the 2.5 Gsym/s signal, while providing an aggregate throughput of 10 Gb/s, is less susceptible than an OOK 10 Gb/s signal to dispersion limitations in the fiber, minimizing the need for dispersion compensation in the system, and in some cases allowing installed links to operate at higher data rates than possible without multilevel signaling. These factors can significantly reduce system costs while realizing high-speed optical links.  
35

The improved spectral efficiency and reduced system costs afforded by multilevel amplitude modulation are offset to some degree by a corresponding

5 degradation in the signal-to-noise ratio (SNR) of the signal due to the reduced energy separation between signals. For example, modeling channel distortions as additive, white Gaussian noise (independent of the transmitted signal), the received power penalty necessary to achieve the same error performance for a multilevel ASK signal compared to an OOK signal with equal symbol rate is described by the equation:

10 
$$\Delta P = -10 \log(2^n - 1)$$

where  $\Delta P$  is the penalty (in dB) and  $2^n$  is the number of levels. This penalty compares the proposed approach using a data rate  $n$  times faster than the baseline OOK modulation. One can also compare the two methods using the same data rate. The power penalty for this case is:

15 
$$\Delta P' = -10 \log([2^n - 1] / \sqrt{n}).$$

The penalty is lower for this constant data rate comparison because the reduced bandwidth for the proposed multilevel scheme allows for higher out-of-band noise suppression. The penalty  $\Delta P'$  does not take into account the effects of dispersion. These effects are negligible at data rates on the order of 2.5Gb/s but can be quite 20 significant at data rates 10Gb/s and higher. Thus, the penalty  $\Delta P'$  is overstating the penalty associated with multilevel signaling because the signal model for the high rate OOK scheme neglects the significant effects of dispersion

Figure 4 is a graph 400 depicting a curve 402 representing an exemplary optical power penalty for OOK and multilevel signals as a function of normalized aggregate data rate. The plot displays the increase in signal power required for 25 multilevel signaling to achieve the same error rate as OOK signaling operating at the same data rate. If the power penalty associated with multilevel optical transmission can be overcome with signal processing gains, this method of data transmission can be a viable, cost effective solution for realizing high-speed fiber optic links. Various 30 embodiments of the present invention are described below and address methods of overcoming this optical power penalty.

### An Exemplary Transmitter

Figure 5 is a block diagram depicting multilevel ASK optical transmitter 500 35 that is an exemplary embodiment of the present invention. The transmitter 500

5 typically comprises an error protection coding (EPC) module 510, an  $n$ -channel encoder 502, a Digital to Analog Converter DAC 504, pre-compensation circuitry 506, and an optical source 508. The combination of the error protection coding (EPC) module 510,  $n$ -channel encoder 502, Digital to Analog Converter DAC 504, and pre-compensation circuitry 506 may be referred to as a symbolizer. The electronics of the  
10 transmitter 500 are termed the "symbolizer", since they generate the  $2^n$  distinct symbols from one or more binary data input streams. The EPC module 510 maps an  $m$ -bit word (that consists of a single bit from each of the  $m$  input data streams) into an  $n$ -bit word where  $n \geq m$ . The data is processed by this module so that when decoded in the receiver, the protected word is robust to bit errors introduced by the  
15 encoding/transmission/decoding process.

For every clock cycle, the encoder 502 converts the protected  $n$ -bit word into a second "error-resistant"  $n$ -bit word. Gray codes, such as the Q-Gray code shown in Table 1, are an example of "error-resistant" codes, where Q-Gray codes are defined to be a class of Gray codes satisfying the property that the maximum number of  
20 transitions on each bit is minimized as one cycles through the sequence. This limitation on the maximum number of transitions produces codes that surpass tradition Gray-codes in that the impact of errors in excess of adjacent levels is minimized. For example, the Q-Gray code in Table 1 has a maximum of four transitions (which is the minimum value possible) on any bit as one cycles through the  
25 sequence. The traditional reflected Gray code, however, has eight transitions on the least significant bit and thus does not meet our definition of a Q-Gray code. It should be obvious to one skilled in the art, that a set of equivalent Q-Gray codes that can be formed from the one tabulated in Table 1. The bit columns can be arbitrarily rearranged, the columns can be inverted, and the code can be "rotated" in 16 different  
30 ways, resulting in a total of 6144 equivalent codes that we term "Q-Gray codes". The encoded  $n$ -channels are input to the DAC 504, which generates a  $2^n$ -level electrical signal that can be used to modulate the optical source 508. The optical source 508 could in practice be a directly modulated laser or a laser with an external modulator and can transmit distinct data values (symbols) by transmitting varying levels of  
35 optical intensity over an optical communication medium, such as an optical fiber.

5

**Table 1.** Binary encoding schemes for 16 level transmission.

Transmitted Level	Conventional Binary	Reflected Binary (Gray code)	Q-Gray Code
15	1111	1000	1000
14	1110	1001	1010
13	1101	1011	1110
12	1100	1010	1100
11	1011	1110	0100
10	1010	1111	0101
9	1001	1101	1101
8	1000	1100	1001
7	0111	0100	1011
6	0110	0101	1111
5	0101	0111	0111
4	0100	0110	0110
3	0011	0010	0010
2	0010	0011	0011
1	0001	0001	0001
0	0000	0000	0000

In an exemplary embodiment of the present invention, four digital channels can be input to the EPC module 510. The EPC module 510 makes the data more robust by sending an extra  $n-m$  bits of data for every  $m$  input bits. These redundant error correction (EC) bits allow for the correction by the receiver of bit errors incurred during the encoding/transmission/decoding process. One skilled in the art will recognize that a variety of existing algorithms may be used to accomplish this. Typical algorithms included Reed-Solomon codes, Reed-Muller codes, block codes, convolutional codes, and trellis codes to name a few. The additional data introduced

5 by the EPC module may be addressed either by increasing the system clock rate or by using more than four channels throughout the remainder of the system. Both addresses are transparent to the proposed invention as they simply correspond to a change in an operational parameter. In particular, increasing the clock rate involves sending pulses with a shorter duration, and using more channels involves using a  
10 larger value for  $n$ . Thus, no generality is lost in assuming that the clock rate is increased and number of data channels is kept at four for the purpose of describing the invention.

The EPC module 510 feeds the processed data into the encoder 502. The four encoded channels can then be input to the DAC 504 and converted to one of 16  
15 possible amplitude levels for a four times increase in data throughput. The encoding function of the four-channel encoder 502 as well as the corresponding DAC output is summarized in Table 2.

**Table 2.** Q-Gray encoding and DAC output.

Input Four-Bit Word	Q-Encoded Four-Bit Word	Level Output by DAC
1111	1000	8
1110	1010	10
1101	1110	14
1100	1100	12
1011	0100	4
1010	0101	5
1001	1101	13
1000	1001	9
0111	1011	11
0110	1111	15
0101	0111	7
0100	0110	6
0011	0010	2

0010	0011	3
0001	0001	1
0000	0000	0

5

Pre-distortion of the transmitted data can help compensate for non-ideal link frequency response and for some classes of link non-linearities, effectively reducing pattern-dependent errors in the transmitted data. Hence, this technique is often referred to as pre-compensation. This pre-distortion (as described below) may operate at the analog/symbol level as shown in Figure 5 or on the digital level as shown in the transmitter 600 of Figure 6. Either method can be algorithmically identical and selected based on the cost of implementation. An exemplary linearization circuit block 512, 602 is shown in both Figure 5 and Figure 6. These circuits can linearize the optical source, which is expected to be the most nonlinear element in the optical link. The functional blocks, less the optical source shown in Figures 5 and 6, can be integrated into one circuit or multichip module.

A number of coding options exist to accomplish the desired EC necessary to compensate for the power penalty associated with multilevel amplitude modulation. The EPC 510 will be responsible for implementing such algorithms. An exception to this is the implementation of Gray codes (as described in U.S. Patent No. 2,632,058), which are an example of block coding with  $m=n$ . The Gray code can be implemented in the encoder since it corresponds to a one-to-one mapping, which can be implemented with a small logic circuit. In the '058 patent referenced above, a method of encoding binary notation is described such that adjacent words in the code are differentiated by a change in only one bit. This method can be distinguished from conventional binary notation where adjacent words often differ by several bits. For example, the binary equivalent of 7 in a four-bit word is 0111. The binary equivalent of 8 (an adjacent "word" to 7) is 1000; each of the four bits is reversed. Although the teaching in the '058 patent pertains to pulse code modulation, the same principles can be applied to multilevel amplitude modulation. If conventional binary notation is used to encode four data streams into a single 16-level stream, the bit error rate (BER) of the channels will be especially sensitive to those transitions between adjacent levels that involve a change of greater than one bit. Thus, Gray codes can reduce bit error

5      rates (without the addition of redundant EC bits) in systems where the channel rate is increased using multilevel encoding. As stated above, Table 1 relates a conventional binary encoding for a 16-level (four channels) transmission to various Gray code encoding schemes. Each of the digits in the four-bit words shown in the table represents a transmitted bit from one of the four independent data streams. The  
 10     binary reflected notation is described in the '058 patent. The alternative Gray code (which we will denote as Q-Gray code for simplicity) is presented in the table as an alternative embodiment of the Gray code implementation for multilevel amplitude modulation. In addition to the adjacent levels differing by only one bit, the alternative code can further enhance channel BERs because, for each individual channel, several  
 15     adjacent levels do not effect a change in the transmitted bit value for that channel.

The encoders (502, 603) depicted in Figure 5 and Figure 6 can perform, among other things, the encoding function described in Table 2. Those skilled in the art will understand that various combinational logic circuits can be designed to perform an encoding function. Figure 8 is a block diagram depicting an exemplary embodiment of a DAC 800, which can best be used to directly drive a laser diode.  
 20     The circuit of Figure 8 is similar to the conventional laser driver circuit 800 of Figure 7 with the exception that the differential switch transistors (e.g., 802) and modulation current source (e.g. 804) are divided up into  $N$  appropriately binary-divided parts. In this manner, the multilevel driver 800 is anticipated to exhibit very similar speed properties as a conventional driver 700.  
 25

During circuit operation, the individual  $N$  bits ( $A_i$ ) of a binary encoded binary word,  $A$ , are individually applied to the respective differential switch inputs (e.g., 806). A binary word is assumed to be made up of  $N$  bits ( $A_N, A_{N-1}, \dots, A_2, A_1$ ) of value 0 to 1, and the decimal value,  $D_w$ , of the word is shown in Equation 1:

$$30 \quad D_w = A_N \cdot 2^{N-1} + A_{N-1} \cdot 2^{N-2} + \dots + A_2 \cdot 2 + A_1 = \sum_{i=1}^N A_i \cdot 2^{i-1} \quad (1)$$

This is the conventional definition of a binary encoded word. The corresponding differential inputs for each  $i$ th binary bit,  $A_i$ , are labeled  $V_i$  and  $V_i'$  to represent the fact that the actual voltages used to represent the binary levels are not 0 and 1. Nevertheless, it is assumed that the differential switch is driven appropriately for one  
 35     of each of the switches' transistors to be "on" for any given logic state.

5           The current sources  $I_1$  through  $I_N$  are binary weighted as follows in Equation  
2:  
2:

$$I_i = \frac{I_{\text{mod}}}{2^N - 1} \cdot 2^{i-1}, \quad (2)$$

10           where  $I_{\text{mod}}$  is the modulation current of the traditional laser driver circuit. The  $N$   
individual bits of the applied binary word drive the respective switch that controls the  
current source determined in Equation (2). This results in a total current,  $I_T$ , of  
Equation 3:

$$I_T = \sum_{i=1}^N A_i \cdot I_i = \sum_{i=1}^N A_i \cdot \frac{I_{\text{mod}}}{2^N - 1} \cdot 2^{i-1} \quad (3)$$

Grouping the constant terms in Equation (3) gives the definition of total current  
shown in Equation 4:

$$15 \quad I_T = K \cdot \sum_{i=1}^N A_i \cdot 2^{i-1} \quad (4)$$

in which the constant  $K$  is defined in Equation 5:

$$K = \frac{I_{\text{mod}}}{2^N - 1} \quad (5)$$

Comparing Equation (4) to Equation (1) shows that the resulting total output current,  
 $I_T$ , is a perfect analog representation of the decimal value of the binary word. This  
20           circuit 800 effectively forms a large-current digital-to-analog converter.

The speed of the multilevel driver 800 can be similar to the speed of the  
conventional driver 700 if the differential switches 802 and current sources 804 are  
appropriately scaled for device size. The size of the transistors 802 used for the  
circuit 800 directly impacts circuit speed. In general, the smaller the transistors used  
25           to perform a circuit's function, the faster the circuit. For the  $i$  current paths of the  
modulator, the current level through each path is proportional to  $2^{i-1}$ . Therefore the  
transistor sizes,  $S_i$ , of both the differential switch 802 and current sources 804 can be  
scaled by as shown in Equation 6:

$$S_i = \frac{S_o}{2^N - 1} \cdot 2^{i-1}, \quad (6)$$

5 where  $S_o$  is the size of the conventional laser drivers transistors (FET width or BJT area). With this device scaling, the total device size of all current paths, which is a good indicator of circuit speed is defined in Equation 7:

$$S_T = \sum_{i=1}^N S_i = \frac{S_o}{2^N - 1} \sum_{i=1}^N 2^{i-1} \equiv S_o \quad (7)$$

10 The total device "size" of all current paths is identical to the conventional driver circuit 700 and therefore should exhibit a very similar circuit speed.

15 The plurality of current sources 804 shown in Figure 8 can be conveniently realized by using scaled current mirrors as shown in Figure 9. In this circuit 900, the BJT area is scaled to provide precise current scaling. A current injected into the reference BJT 902 will be "mirrored" as per area ratios to the multiple BJT current source outputs 904-908. The injected current on the reference BJT 902 sets the current range for the circuit 900. The actual input current used to control the plurality of sources can be scaled as desired as shown by a scaling factor  $\beta$ . If FET devices are used to realize this circuit, the FET widths can be similarly scaled.

20 This circuit 900 is a high-output-current digital-to-analog converter, which can be applied to a variety of applications including the driving of laser diodes. In particular, if the laser diode shown in Figure 8 was replaced with a load resistor, the binary controlled current will be converted to a voltage allowing for the drive of other voltage-controlled optical modulators (e.g., the Mach-Zehnder modulator). This exemplary DAC 900 can be used to directly drive an optical source or drive other pre-compensation networks, which subsequently drive the optical source.

25 The pre-compensation blocks shown in Figure 5 and Figure 6 will appropriately modify the transmitted signal to produce a faithful output at the receiver. An exemplary pre-compensation block 506 comprises a pre-distortion circuit 511 and a linearizer 512. The pre-distortion circuit 511 can modify the transmitted signal based on knowledge of prior data and known link linear and nonlinear performance. The linearizer circuit 512 can present a nonlinearity, which ideally exactly counteracts the nonlinearities of the optical source. Furthermore, the pre-compensation block, which operates at a particular symbol rate, also enables the simultaneous optimization of the transmitted phase when the information is contained

5 in the symbol amplitude. Thus, well known modulation techniques, such as duobinary, can be readily combined with the pre-compensation function.

Figure 10 is a block diagram depicting an exemplary embodiment of a pre-distortion channel compensator 1000 for the multilevel transmitter 500 shown in Figure 5. In this embodiment, the amplitude of the symbol to be transmitted can be  
 10 modified based on the amplitudes of preceding and succeeding symbols to ensure that the receiver and decoder are able to accurately detect the proper symbol amplitude after transmission. The incoming electrical multilevel data stream is tapped (i.e., interrogated) and subsequently delayed with three separate delays so that all three signals can be analyzed. As an example, each delay may consist of a transmission  
 15 line. The delay associated with each tap ( $\tau$ ,  $2\tau$ , and  $3\tau$ ) is shown in Figure 10 with  $\tau = 1/(\text{symbol rate})$ . Thus each tapped delay line isolates one of a set of adjacent symbols to be transmitted. Specifically, the  $2\tau$  tap, for a given clock cycle, represents the multilevel symbol to be transmitted during that clock cycle, while for the same clock cycle, the  $\tau$  and  $3\tau$  taps represent the succeeding and preceding symbols in the data stream, respectively. This concept is illustrated in Figure 11, where in a multilevel  
 20 amplitude modulated signal 1100 is depicted.  $S_n$  represents the symbol to be transmitted, and  $S_{n+1}$  and  $S_{n-1}$  represent the succeeding and preceding symbols in the data stream.

Returning to Figure 10, each of the differential amplifiers A, B, and C linearly  
 25 amplifies the difference between two of the tapped symbols. The function of each of these amplifiers is represented by the Equations 8-10 below:

$$G_A(S_{n+1} - S_n) = A \cdot (S_{n+1} - S_n) \quad (8)$$

$$G_B(S_n - S_{n-1}) = B \cdot (S_n - S_{n-1}) \quad (9)$$

$$G_C(S_{n+1} - S_{n-1}) = C \cdot (S_{n+1} - S_{n-1}) \quad (10)$$

30 where  $G_k$  is the gain of the amplifier (with  $k = A, B$ , or  $C$ ).

The differential amplifiers D, E, and F are second order amplifiers and operate by amplifying the square of the difference between two of the tapped symbols. The function of each of these amplifiers is described by Equations 11-13:

$$G_D(S_{n+1} - S_n)^2 = D \cdot (S_{n+1} - S_n)^2 \quad (11)$$

5

$$G_E(S_{n+1} - S_n) = E \cdot (S_{n+1} - S_n)^2 \quad (12)$$

$$G_F(S_{n+1} - S_n) = F \cdot (S_{n+1} - S_n)^2 \quad (13)$$

The differential amplifier G shown in Figure 10 indicates that higher order functionality is easily included in this signal-processing filter. Any two of the tapped symbols can be input to the amplifier such that amplification of order  $q > 2$  is performed on the difference between the symbols. The specific inputs are not specified in the figure to indicate that any of the symbols may be input to the amplifier. It should be clear to one skilled in the art that this design lends itself to the inclusion of additional higher-order (i.e.,  $q > 2$ ) differential amplifiers (H, I, J, etc.), which are not explicitly shown in the figure.

15

The element  $\Sigma_1$  sums the output symbols from the differential amplifiers A through G, generating the polynomial  $\mathfrak{R}$  shown in Equation 14:

$$\mathfrak{R} = A \cdot (S_{n+1} - S_n) + B \cdot (S_n - S_{n-1}) + C \cdot (S_{n+1} - S_{n-1}) \quad (14)$$

$$+ D \cdot (S_{n+1} - S_n)^2 + E \cdot (S_n - S_{n-1})^2 + F \cdot (S_{n+1} - S_{n-1})^2 + G \cdot (\dots)^q$$

As an example,  $\Sigma_1$  may be an adder or a power combiner.

20

The element  $\Sigma_2$  (which, as an example, may be an adder or a power combiner) sums  $\mathfrak{R}$  with the symbol to be transmitted ( $S_n$ ) in the data stream. For this reason, the data stream must be delayed by an amount equivalent to the delay applied to the tapped  $S_n$  symbol. For the case shown in Figure 10, the necessary delay would be  $2\tau$ . In addition, the clock signal used in conjunction with a timing recovery circuit may be required at  $\Sigma_2$  in order to ensure proper synchronization of the data stream with  $\mathfrak{R}$ . Thus, the circuit 1000 shown in Figure 10 will transmit the symbol  $S'_n = \mathfrak{R} + S_n$  for each symbol in the data stream. In this way, the symbol  $S_n$  is predistorted by the amount  $\mathfrak{R}$  to ensure that  $S_n$  is accurately received after transmission.

30

Figure 10 depicts an exemplary embodiment of a generalized precompensation technique. This technique may include, for example, corrections that are proportioned to the difference between the preceding and succeeding symbols, identified with the coefficient C in Figure 10. It will be appreciated by those skilled in the art that higher order corrections are possible. As long as the channel distortions are "well-behaved,"

- 5      the number of correction terms in  $\mathfrak{R}$  will be limited and the circuit implementation simplified.

Those skilled in the art will appreciate that the method of precompensation described above also may be implemented with a pre-determined, stored digital mapping function or lookup table. In such a case, the appropriate modification to the  
10     transmitted output symbol, as determined by the lookup table, may be based on characteristics of the symbol itself as well as those of one or more preceding and succeeding output symbols. For example, a 16 level system ( $n=4$ ) which interrogates 3 input symbols, (i.e., the symbol to be transmitted and the preceding and succeeding pulse) requires 4096 table entries. For high symbol rates (e.g., 2.5 Gsym/s and  
15     greater), the implementation of a large lookup table can become increasingly complex. Hence, the previously described analog circuit embodiment, which is designed to approximate the functionality of a lookup table, may be preferred. In either case, the lookup table entries or the coefficients of the circuit implementation may be dynamically updated to maintain the desired system performance.

20     Figure 12 is a block diagram depicting an alternative embodiment of the precompensation filter 1200. While similar in operation to the exemplary embodiment depicted in Figure 10, this exemplary embodiment has integrator circuits A 1202 and B 1204 integrated with the delay lines corresponding to the preceding and succeeding symbols in the data stream. These integrator circuits 1202, 1204 have  
25     time constants that are equal to some value slightly larger than the inverse of the symbol rate. Thus, the integrations performed by the circuits act over a period greater than one symbol length, effectively extending the set of symbols used to determine  $\mathfrak{R}$  to include information regarding symbols just beyond the boundary of the set. For example, the precompensation factor for the embodiment shown in Figure 12 can be  
30     expressed as shown in Equation 15:

$$\begin{aligned} \mathfrak{R} = & A \cdot \left( \int S_{n+1} dt - S_n \right) + B \cdot \left( S_n - \int S_{n-1} dt \right) + C \cdot \left( \int S_{n+1} dt - \int S_{n-1} dt \right) \\ & + D \cdot \left( \int S_{n+1} dt - S_n \right)^2 + E \cdot \left( S_n - \int S_{n-1} dt \right)^2 + F \cdot \left( \int S_{n+1} dt - \int S_{n-1} dt \right)^2 + G \cdot (...)^q \end{aligned} \quad (15)$$

35     The limits of integration in the above expression can be set to some interval of time greater than the inverse of the symbol rate. In this way, the integration path is extended beyond the bit length of the symbol in the integrand in order to include

5 information regarding neighboring symbols in the data stream. Thus, the expression above, in reference to Figure 12 now takes into account information regarding the symbols  $S_{n+2}$  and  $S_{n-2}$ , which are beyond the set of symbols  $\{S_{n-1}, S_n, S_{n+1}\}$ . The integrated symbols along with the symbol  $S_n$  can be amplified (as before) by linear and higher order amplifiers. As in the previous case, synchronization of the data  
10 stream and  $\Re$  may be required at  $\Sigma_2$ .

Figure 13 is a pair of graphs 1300, 1350 depicting typical light output versus input current of a laser diode, and control voltage of an M-Z modulator. Both device classes suffer from a random offset (i.e. termed the threshold current on a laser), which can be handled by a simple offset current or voltage by the driver circuit. The  
15 objective here is to linearize these transfer curves like the linear ones labeled as "B" in each graph.

Figure 14 is a block diagram of linearization circuit 1400 for a laser diode that is an exemplary embodiment of the present invention. Figure 15 is a block diagram of linearization circuit 1500 for a voltage driven optical modulator such as a (M-Z) Mach-Zehnder modulator. For both of these approaches, a linearization circuit 1400,  
20 1500 is added to provide a predistortion to the drive current or voltage to linearize the resulting optical output. To linearize a laser diode, the linearization circuit subtracts an "error" current,  $I_e$ , from the drive current,  $I_d$ , such that a laser terminal current,  $I_d'$ , is adjusted to produce a light output linear with  $I_d$ . Similarly, to linearize a voltage  
25 driven modulator 1502 as shown in Figure 15, a linearization circuit 1500 is added to appropriately adjust the voltage to result in a linear output light level in terms of the drive voltage  $V_m$ .

Figure 14 depicts an exemplary circuit diagram of a laser diode linearization network that is an exemplary embodiment of the present invention. A special  
30 nonlinear element (labeled NLE) 1404 produces a linear light output in terms of the drive current,  $I_d$ . This linear light output,  $L$ , can be described in Equation 16 as:

$$L = \begin{cases} 0 & \text{for } I_d < I_o \\ \alpha \cdot (I_d - I_o) & \text{for } I_d \geq I_o \end{cases} \quad (16)$$

in which  $L$  is the light output,  $\alpha$  is the slope of the output versus drive current, and  $I_o$  is the zero light output current. The light output produced by the laser diode is some  
35 nonlinear function,  $L_D(I_d')$ , of the laser's drive current,  $I_d'$ , as shown by Equation 17:

5

$$L = L_D(I_d) \quad (17)$$

The objective is to have  $I_d'$  be a function of  $I_d$ , such that Equation (16) and Equation (17) are identical, or algebraically for  $I_d > I_o$ :

$$\alpha \cdot (I_d - I_o) = L_D(I_d') \quad (18)$$

In practice, this equality can only be maintained over a limited device operating range. By current conservation:

$$I_d' = I_d - I_e \quad (19)$$

where  $I_e$  the nonlinear element's terminal current which is a function the element's terminal voltage,  $V$ . The circuit dictates that  $V$  is:

$$V = V_d(I_d) + R_d \cdot I_d \quad (20)$$

15 in which  $V_d(I_d)$  is the laser diode's junction voltage.

After combining Equations (18), (19), and (20), and simplification to eliminate  $I_d$ , the necessary parametric function form for the nonlinear element required to linearize the light output is shown in Equation 21:

$$I_e(V_d(I_d) + R_d \cdot I_d) = \frac{L_D(I_d)}{\alpha} - I_d + I_o \quad (21)$$

20 Since the laser characteristics  $V_d(I)$ ,  $R_d$ , and  $L_D(I)$  are known and  $I_o$  and  $\alpha$  can be selected as desired, the necessary  $I_e(V)$  for linear operation is now known by this equation.

25 Referring to Equation (21), the product of  $R_d$  and  $I_d$  is added to the laser diode's operating voltage in the nonlinear element's terminal voltage (argument on the left-hand side of equation). This allows for the nonlinear element to be realizable using a simple circuit as presented below.

Linearization of a voltage controlled light modulator is similarly performed as depicted in Figure 15. In the circuit 1500 depicted in Figure 15, a nonlinear element (NLE) 1504 has a voltage dependant current, which causes an input-voltage dependent voltage drop across the resistor,  $R_m$ . This voltage drop across  $R_m$  is designed to precisely counteract the nonlinearity of the modulator. The objective is to provide a light output, which is linear with drive voltage:

5

$$L = \begin{cases} 0 & \text{for } V_m < V_o \\ \beta \cdot (V_m - V_o) & \text{for } V_m \geq V_o \end{cases} \quad (22)$$

The light output from the modulator is determined by some known nonlinear function,  $L_M$ :

$$L = L_M(V_m') \quad (23)$$

Equating Equations (22) and (23), for  $V_m > V_o$ :

10

$$\beta \cdot (V_m - V_o) = L_M(V_m') \quad (24)$$

From Figure 15, the voltage,  $V_m'$ , across the nonlinear element is:

$$V_m' = V_m - R_m \cdot (I_e(V_m') + I_m(V_m')) \quad (25)$$

in which  $I_m(V)$  is the modulator's current and is zero for many voltage-controlled modulators. Equations (23), (24), and (25) can be solved for  $I_e$  in terms of the 15 modulator voltage  $V_m'$  to give:

$$I_e(V_m') = \frac{1}{R_m} \left( \frac{L_M(V_m')}{\beta} + V_o - V_m' \right) - I_m(V_m') \quad (26)$$

Equation 26 gives the functional form of  $I_e$  required for linear light output with  $V_o$  and  $\beta$  being free scalar parameters.

20

Thus, the necessary current voltage characteristics of the nonlinear element have been determined, but not the nonlinear element itself. Preferably, the nonlinear element is passive (plus diodes). This will restrict the nonlinear element to only exhibit a positive differential resistance/conductance. That is, the current can only increase (or remain constant) with increasing applied voltage. This places restrictions on the resulting modulation sensitivities ( $\alpha$  and  $\beta$ ).

25

For the laser diode linearization circuit, differentiating Equation (18) and solving for the partial derivative of  $I_e$  with respect to  $I_d'$  gives Equation 27:

$$\frac{\partial I_e}{\partial I_d'} = \frac{1}{\alpha} \frac{\partial L_D(I_d')}{\partial I_d'} - 1 \quad (27)$$

The left-hand side of Equation (29) must be positive since the differential resistance of the series combination of the laser diode and resistor,  $R_d$ , must be positive and as

- 5 discussed above the conductance of the nonlinear element must be positive.  
Algebraically,

$$\frac{\partial I_e}{\partial I_d} = \frac{\partial I_e}{\partial V} \frac{\partial V}{\partial I_d} \geq 0 \quad (28)$$

Combining Equations (27) and (28) gives:

$$\alpha \leq \frac{\partial L_D(I_d)}{\partial I_d} \quad (29)$$

- 10 for all operating currents,  $I_d'$ . This sets the linearized slope efficiency to be less than or equal to the original laser slope efficiency.

Similarly, for the voltage controlled optical modulator, assuming that the modulator conducts no current:

$$\beta \leq \frac{\partial L_M(V_m)}{\partial V_m} \quad (30)$$

- 15 for all modulator voltages,  $V_m'$ . If the modulator conducts current, the slope efficiency will be lower because of the losses introduced by  $R_m$ .

An exemplary embodiment of the nonlinear element 1600 is shown in Figure 16. For simplicity and ease of manufacture, the circuit 1600 comprises series-connected resistor and diode networks. These networks are biased to a set voltage 20 (labeled  $V_{nx}$ ), which along with the diode built in voltage sets a turn-on voltage where at above or below (depending on the diode polarity) the resistor is added into the circuit. The nonlinear response of typical configurations of each type of branch network is illustrated in the graph 1700 depicted in Figure 17. Note that the basic I(V) characteristic of these networks is two linear segments separated by a voltage 25 breakpoint. An appropriately selected plurality of these networks allows the synthesis of the shape of an arbitrary I(V) curve with the restriction of positive slope and the addition of an arbitrary offset current or voltage. This offset can fortunately be absorbed within the arbitrary offsets  $I_o$  and  $V_o$ . The actual synthesis of the network is difficult analytically due to the lack of orthogonality of the resulting basis functions. 30 Nevertheless, trial and error techniques with conventional circuit simulation programs can easily yield an effective network. Due to the basic I(V) characteristics of the

- 5 branch networks (linear segments with voltage breakpoint), the resulting approximation will be a so-called "piece-wise linear approximation".

In actual implementation, voltage sources with the single series resistor configuration may not be used. Instead, a Thevenin equivalent network may be synthesized from the system power supply and a series combination of two resistors.

- 10 The resistors  $R_1$  and  $R_2$  are selected such that:

$$V_A = \frac{R_1}{R_1 + R_2} V_{cc} \quad \text{and} \quad R_A = \frac{R_1 \cdot R_2}{R_1 + R_2} \quad (31)$$

where  $R_1$  is connected from ground to the diode and  $R_2$  is connected from the  $R_2$  diode junction to  $V_{cc}$ .

- The approach described herein addresses static linearization. The 15 embodiments shown are anticipated to be integrated in microelectronic circuits allowing for very low parasitics and high-quality microwave diodes. Therefore, the linearization circuit may be expected to have a very large bandwidth. It may be assumed that the dynamic response of the laser diode or optical modulator is the same as static up to the operating speed. This is justified by the fact that an optoelectronic 20 or electronic device's operational bandwidth is roughly defined by the frequency where the dynamic performance is no longer similar to the static and it is assumed that the device being linearized is being operated at a frequency within its bandwidth. Additionally, it should be obvious to one skilled in the art that reactive impedance matching can occur between the device and the linearization network to help mitigate 25 this issue.

- In summary, the linearization network illustrated in Figure 14 works by a 30 nonlinear element shunting the appropriate amount of current from a drive current to result in a linear light output of a nonlinear current drive optical modulator device. Similarly, as illustrated in Figure 15, a voltage controlled nonlinear optical modulator device, is linearized by the addition of a series resistance, which converts the nonlinear shunt current into a nonlinear voltage drop to result in a linear light output. The topology of the nonlinear element is illustrated in Figure 16. In this circuit a plurality of shunt connected diode-resistor circuit branches are selected to synthesis the required nonlinear current vs. voltage curve to linearize the optical modulator.

5        The light source is assumed to be amplitude controlled and of adequate coherence to be used in WDM systems. It is desired that the source be as linear as possible, though as just described in the previous section, linearization networks can be used to improve linearity. The light source will need to have an electrical bandwidth commensurate with the symbol rate of the communication link. This will  
10      be much lower than the link's aggregate data rate and therefore represents significant cost advantage at moderate speeds (less than or equal to 10 Gb/s) and enabling technology at high data rates (over 40 Gb/s). Preferred light sources include direct modulation of laser diodes, and externally modulated laser sources (i.e., Mach-Zehnder, or Electro-Absorptive modulators).

15

### An Exemplary Receiver

Figure 18 is a block diagram depicting a multilevel ASK optical receiver 1800 that is an exemplary embodiment of the present invention. The receiver 1800 typically comprises an optical detector 1802, distortion post-compensation circuits 20 1804, an Analog to Digital Converter (ADC) 1806, an  $n$ -channel decoder 1808, and an error protection decoding (EPD) module 1816. The combination of the distortion post-compensation circuits 1804, an Analog to Digital Converter (ADC) 1806, an  $n$ -channel decoder 1808, and an error protection decoding (EPD) module 1816 may be referred to as a desymbolizer. The electronics of receiver 1800 are termed the 25 "desymbolizer", because they convert the received symbols back into one or more binary output data streams. The optical detector 1802 converts a  $2^n$ -level optical signal into a  $2^n$ -level electrical signal, which is then processed by post-compensation circuitry 1804. The post-compensation circuitry 1804 comprises an adaptive equalization means 1810 as well as an optimal detection filtering means 1812. The 30 output of the compensator 1804 is input to an ADC 1806, which converts the  $2^n$ -level signal into  $n$  digital data streams. The ADC 1806 can employ a novel statistical automatic threshold determination means, which will allow for compensation of some of the link nonlinearities. These  $n$  channels are input to a decoder 1808, which converts a coded  $n$ -bit word each clock cycle into the corresponding  $n$ -bit word that was initially input to the transmitter encoder shown in Figure 5 and 6. The original 35 data input to the transmitter is then obtained from the EPD 1816 by decoding the error protected data using the redundant bits introduced by the transmitter's EPC 510

5 (Figure 5) to correct errors in the received data. A clock recovery circuit 1814 can be used to generate the necessary timing signal to operate the ADC 1806 as well as output synchronization. In an exemplary embodiment of the multilevel receiver 1800, a 16-level amplitude-modulated signal can be detected by the photodetector 1802 and ultimately converted to four digital data streams in order to realize a four times  
10 improvement in bandwidth of the transmission system. Analog-to-digital conversion and Q-Gray code-based decoding for a 16-level signal are summarized in Table 3. All of these functional blocks, less the optical detector 1802, can be integrated in one circuit or on multi-chip module

**Table 3.** ADC output and Q-Gray decoding

Level Input to ADC	Four-Bit Word Input to Q-Gray Decoder	Four-Bit Word Output from Q-Gray Decoder
15	1111	1000
14	1110	1010
13	1101	1110
12	1100	1100
11	1011	0100
10	1010	0101
9	1001	1101
8	1000	1001
7	0111	1011
6	0110	1111
5	0101	0111
4	0100	0110
3	0011	0010
2	0010	0011
1	0001	0001

0	0000	0000
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5

The optical detector 1802 and following trans-impedance amplifier (TIA) should exhibit good linearity over the entire receiver dynamic range. Fortunately, a conventional PIN detector in conjunction with an analog TIA offers good linearity over wide signal ranges. Additionally, the adaptive thresholding discussed below as well as the pre-distortion discussed above will compensate for system nonlinearities.

10 The TIA is assumed to have a gain control, which will be used to produce a signal output of fixed amplitude.

Figure 19 is a block diagram depicting an exemplary embodiment of a transversal filter 1900. This circuit 1900 forms a classical transversal filter or equivalently a finite impulse response filter (FIR) filter, which can synthesize an arbitrary frequency response based on the tap gains/coefficients. Here, equalizer tap gains can be determined by the output conductance of FETs. Controlling both the size of FET and the gate bias voltages sets the output conductances. These control FETs are appropriately scaled to minimally impact the input signal propagating down the delay transmission line(s). The input is assumed to either be differential or single-ended with the circuit generating an inverted form of the input as shown in Figure 19. This is required to allow for the filter coefficient to be either positive or negative depending on which FET is activated ( $c_i$  or  $c_i^+$ ).

In this circuit 1900, an input signal is divided into two parts. One part propagates down the upper cascade of delay-lines of equal delay 1902; whereas the other part is inverted and propagated down the lower cascade of delay lines 1904. Alternately, a differential signal can be applied to the upper 1902 and lower 1904 delay line cascades without the need for a signal inverting means. The two transmission line cascades can provide a means for supporting both positive and negative gain coefficients. From each junction of the delay-lines a high-input impedance amplifier (e.g., 1906) is used to sample the signal without significantly distorting the signal propagating down the delay-line cascade. From each of these buffers is a FET (e.g., 1908) (drain or source connected), which is used as a variable resistor means. The other terminal (source or drain) of these variable resistance 30 FET's is connected to a common node 1910 at which point signal summation occurs.

5 From this node is a resistor 1912 that is of sufficiently low impedance to mitigate coefficient interdependence, which would be caused by the varying impedance of this summation node as various taps are controlled. The resulting summation is then amplified and output.

10 Figure 20 is a block diagram depicting an adaptive transversal filter 2000 for the multi-level optical transmission system that is an exemplary embodiment of the present invention. In this embodiment, the spectral amplitude of the received symbol is adjusted based on equalizer tap gains which are calculated in the microcontroller 2002 in order to remove the effect of intersymbol interference.

15 The peak voltage of the received signal,  $V_p$  is detected by a diode 2003, capacitor 2006, and resistor 2008. Ideally, with a frequency independent (equalized) channel, the peak voltage would be constant over time. If the optical channel is not equalized, the measured peak voltage will vary with time. This occurs due to the time dependent frequency content of a random data stream. Thus, the sampled peak voltage is measured and fed into the microcontroller 2002 through the ADC 2004. The job of  
20 the microcontroller 2002 is to appropriately select the gain coefficients of the PTF to make the measured peak voltage constant in addition to removing ISI which corrupts the other signal levels in the same manner as the peak. Since there may be no knowledge of the frequency content of the random data at any given time, the measured peak voltage fluctuation can only give a measure of goodness and not direct  
25 knowledge of appropriate PTF settings. Therefore, the microcontroller 2002 must perform a multidimensional optimization ( $4N+2$  variables) to minimize a single scalar quantity. Fortunately, those skilled in the art will realize that many numerical techniques can be brought to bear to solve this problem (e.g., minimum mean-squared error method, gradient methods, bisection, genetic algorithm, etc.). One of the  
30 numerical techniques is employed and the microcontroller 2002 repeats this procedure to determine the appropriate equalizer tap gains (weights).

35 The sampling rate must be adjusted appropriately to the received data stream's random properties. Typically one would sample the data sufficiently fast that the frequency content of the signal (and especially the ISI) is observed. However, the practical maximum sampling rate is limited by the cost of such a high-speed ADC. Nonetheless, one may still observe the effects of ISI through the peak stability or the "wellness" of the measured histogram as described later. Consequently, such a

5 measure of goodness (based on slowly sampled data) may be used in an optimization algorithm to determine the filter coefficients. Effective sample rates of 1/10<sup>th</sup> to 1/100<sup>th</sup> the high-speed data rate should be sufficient in the proposed approach. For example, at 10 Gsym/s data rates, a 10 ns sampling time appears appropriate (1/100<sup>th</sup> of the 0.1 ns bit period). This sampling speed (100 Msps) is readily available using  
10 current technology. A preferred embodiment would AC couple the output of the detector circuit 2010 and peak detect the fluctuation amplitude. Then, the microcontroller 2002 can sample the fluctuation level on demand at a rate commensurate with the control algorithm (< 1 Msps) and optimize the filter coefficients.

15 The output of the microprocessor's 2002 optimization algorithm is fed into DACs 2012 to control the equalizer tap gains by varying the gate voltages of FETs. Equalization filters are known to commonly amplify high-frequency noise. To address this issue, a low pass filter (LPF) 2014 is placed after the equalization filter.

In the embodiment shown in Figure 20, a high-speed multilevel data stream  
20 can be routed through the circuit 2000 on the signal path shown in bold. The high-speed data stream first passes through the programmable transversal filter (PTF) 2016, which frequency equalizes the signal. The high-speed signal can then be amplified as appropriate and low pass filtered (LPF) to minimize that typical noise amplification caused by the PTF 2216. The high-speed data stream is monitored after the PTF 2016  
25 by a simple peak detector circuit comprised of a diode 2003, resistor 2008 and capacitor 2006. The output of the peak detector circuit is appropriately signal conditioned by removing the DC component and again power detected (envelope, Root-Mean-Square (RMS), or other means is sufficient), filtered, amplified and fed to the ADC 2004 of a microcontroller 2002. The microcontroller 2002 samples the  
30 ADC and by an iterative algorithm based on the fluctuations of the envelope of the high-speed signal determines the best settings of 4N+2 DACs 2012, which control the 4N+2 coefficients of the PTF 2016. This allows for the automatic equalization of a high-speed multilevel communication data stream in a means, which does not interrupt the data flow.

35 Figure 21 is a block diagram depicting an exemplary optimal filtering circuit 2100, which can be used at very high data rates. This circuit 2100 uses a novel method for parallel noise filtering and detection implementation using integrate and

5 dump filters (IDFs). IDFs form the optimal correlation detection for simple rectangular data symbols (correlates a rectangle with a rectangle). At high data rates, it is normally difficult to realize IDFs that can "dump" fast enough to correlate the next symbol. The approach described here overcomes this limitation by parallel processing the received data. This approach also provides the additional feature of  
10 allowing for serial to parallel data conversion without requiring an additional demultiplexer circuit in the receiver resulting in receiver simplification. Additionally, this approach reduces the speed requirement of the ADCs 2102, 2104 as each converter samples at a rate reduced by the number of IDF circuits. The approach can be extended to higher orders of parallelism (N channels) depending on the level of  
15 demultiplexing desired as well as the speed restrictions of available ADC circuits.

The received signal from the equalization filter or receiver is split and fed into the two IDFs. The dump filters consists of an integrator (i.e. RC circuit) and switch (i.e. transistor). The number of dump filters employed may vary depending on the data rate and the limitations of component performance. A clock is used for the  
20 dumping pulse of the integrator and will be extracted from the received signal using a clock recovery circuit followed by a divide-by-two frequency divider. A clock recovery circuit can be implemented using edge detectors with phase-locked loops or bandpass filters and comparators. With two IDFs, the recovered  $\frac{1}{2}$  clock and inverted  $\frac{1}{2}$  clock signals are adequate to operate the IDFs switches as well as the sample-and-hold (SH) circuits or track-and-hold circuits, which hold the result of the IDFs at the  
25 end of the symbol period for thresholding by the analog-to-digital converters. The data stream is integrated during alternate symbol periods (clock/2) in the IDF filters. This allows for parallel operation resulting in the demultiplexing of the data stream into even and odd symbol data streams. Then, the even and odd data streams can be  
30 sampled and multilevel thresholded by the SH and ADC. The resulting binary signals can be sent to latches to temporally align the results from the two parallel channels. The result is the thresholded output of two symbols once every two-symbol periods. The specific clock pulses used are not shown in Figure 21 due to the hardware  
35 specific nature of the ADC and SH circuits. In general terms, after the end of a given symbol period, the active IDF filter is sampled by the corresponding SH and the corresponding ADC is initiated. Simultaneously, the other IDF filter is made active and begins to perform the correlation of the input signal. This process is continued

5 with each channel (signal path comprised of an IDF, SH and ADC) processing alternate symbols.

Table 4 shows the sequence of events during several symbol periods. The “\*” represents the SH sample point. Note that the latched outputs are both valid over any given symbol period.

10

**Table 4. Timing diagram for a two-channel receiver around the reception of the  $i$ th bit.**

<b>Circuit</b>	<i>Symbol Period</i>			
	$i - 1$	$i$	$i + 1$	$i + 2$
IDF 1	Dump	Active	Dump	Active
SH 1	Hold $i - 2$	*	Hold $i$	*
ADC 1	Convert $i - 2$		Convert $i$	
Latch 1	Valid $i - 4$	Valid $i - 2$		Valid $i$
IDF 2	Active	Dump	Active	Dump
SH 2	*	Hold $i - 1$	*	Hold $i + 1$
ADC 2		Convert $i - 1$		Convert $i + 1$
Latch 2	Valid $i - 3$		Valid $i - 1$	

This approach can be extended to an arbitrary number of channels allowing for  
15 additional speed-performance reduction of the components in each channel as well as for higher levels of demultiplexing.

Figure 23 is a block diagram depicting an exemplary  $N$ -channel filter 2300. Additional channels will require correspondingly increased complexity clock generation as illustrated in Figure 22. A multiphase clock must be used to properly  
20 sequence through operation of the multiple IDF, SH, and ADC functions.

Generally, the  $N$ -channel filter 2300 operates by sequentially activating the IDF circuits 2302 for one symbol period each. At the end of the symbol time, the SH (e.g., 2304) (sample-and-hold or track-and-hold circuits) holds the result of the correlation function performed by the IDFs. The ADC is then triggered and performs  
25 the multi-level thresholding. When the ADC is complete (should be completed in less than  $N$  symbol times), the result is latched into the first set of latches. After all  $N$

5 channels have valid results; the final  $N$  symbol-result is latched into the output latches. The final  $N$  symbol-results remain valid for  $N$  symbol time periods or equivalently until the next  $N$  symbols are processed. This system forms a pipelined detection approach, which significantly alleviates the speed requirements of the ADCs.

10 The Analog-to-Digital Converter (ADC) (e.g., 2306) may be a conventional uniformly-leveled converter of adequate speed and resolution or the preferred embodiment described below. Since the ASK signal may be significantly distorted by the nonlinearities of the optical link, the received levels may no longer be uniformly spaced during detection at the receiver.

15 A simulated multi-level eye diagram of a 16-level signal transmitted through a hypothetical fiber link (10 Gb/s optical link sent through a 140 km fiber length with a single EDFA) is shown in Figure 24. This simulation illustrates the difficulty in determining the thresholds for multilevel data streams. From this simulation, it is apparent that the eyes are non-uniform in noise and level after generation, 20 transmission, and detection in an optical system. It is desired to have voltage detection thresholds centered in the statistical center of each of the 15 "eyes". Since the eyes are no longer uniformly distributed in voltage, a simple conventional direct ADC at the minimum number of bits ( $\log_2(16) = 4$  in this case) is no longer possible. Hypothetically, the received voltage signal could be digitized at a higher resolution 25 (additional bits) and signal processing applied to determine the correct level. Unfortunately, at the targeted symbol rates of many optical systems (i.e. OC-192 at 10 Gb/s) this would require order-of-magnitude speed improvements of readily available ADC and signal processing technologies.

For this exemplary embodiment, the received analog signal is sampled at 30 random points in time and a histogram of the measured voltages is formed as illustrated in Figure 24. This histogram is comprised of a finite number of the most recent "n" samples. As a new sample is determined, the oldest is removed from the sample set. A simple computer search algorithm can then be used to track the center of the eyes for the statistically optimized threshold/decision point for the receiver decision circuit(s).

5        These temporally random samples must be performed at a voltage resolution in excess of the number of levels used in the high-speed data transmission. In particular, in order to determine the location of the peaks and valleys of the resulting histogram, the Nyquist theorem dictates that the sample resolution be as a minimum twice that of the number of data levels in the high speed data stream (i.e. 5 bits for 16  
10      levels). In practice, ADC technology is readily available to allow for significant voltage resolution over-sampling (say 14 bits).

Ideally samples would occur at times centered temporally in the high-speed data stream's eyes. This would require critical timing requirements and therefore not be expected to be cost effective. Instead, the voltage samples can be easily made at  
15      random times thereby allowing for the elimination of all critical timing circuitry. The result of random signal voltage sample times is similar to the ideal sampling case due to the larger probability of sampling during a signal transition. This results in a data "floor" in the histogram, which can be easily removed during subsequent signal processing. Random sampling for this application means random to the high-speed  
20      data rate. This can be achieved by using a periodic sample rate, which is not harmonically related to the high-speed data rate. The actual average sample rate of the random voltage samples is dictated by the threshold update speed desired. If the communication channel is expected to vary quickly with time, the sample rate must be correspondingly high. As an example, assuming that the channel varies with a 10 ms  
25      characteristic time and 1000 samples forms the histogram; average conversion speed only need be 100,000 samples per second.

This approach can additionally provide information of the "wellness" of the received signal. For example, the ratio of the number of samples within the eyes to the peaks between the eyes will relate directly to error rate. Additionally, these types  
30      of ratios along with measured signal levels would provide very useful information to select the operating point of programmable analog signal processing modules prior to this process. For example, the tap weighting coefficients of a programmable delay line equalization filter could be adjusted for maximum data "eye-opening". Advantageously, this approach can be applied to the optimal detection of multi-level  
35      signals of any number of levels (2 to infinity).

Figure 25 is a block diagram depicting an exemplary multi-level receiver  
2500. The diagram is shown for a 4-level receiver, but it should be obvious to one

5 skilled in the art that this circuit can be readily extended to any number of levels. For  
4-levels ( $2^n=4$ ), there is necessarily 3 (i.e.,  $2^n - 1$ ) voltage decision levels. These  
levels are determined by the Digital Signal Processor (DSP) 2502 based on the  
sampled voltage levels.

Specifically, the DSP 2502 would sample the received analog voltage by  
10 triggering the sample-and-hold circuit 2504 or equivalently a track-and-hold circuit at  
some time random in relation to the received data stream. The sample/track-and-hold  
circuits 2504 will necessarily have a capture bandwidth commensurate with the high-  
speed data stream, but will only need to be able to sample at rate much lower than that  
of the high-speed data stream. The DSP 2502 would then trigger the ADC conversion  
15 and record the resulting voltage. The DSP 2502 would continue this process until  
adequate statistic information can be gathered to determine the appropriate decision  
levels. Typical time sample set sizes are expected to be on the order of 100 to 1000,  
though larger or smaller sample sizes can also be selected. The actual sample size  
should be adequate to determine the resulting Gaussian probability peaks with  
20 adequate accuracy to sufficiently determine the eye centers. When a new sample is  
recorded, the oldest will be rejected from the sample set. The statistical analysis will  
be continually performed; thereby adjusting the decision levels in real time to  
compensate for time varying distortion/noise of the received signal. Additionally, the  
“wellness” of the data may also be used to feedback control signals to analog signal  
25 conditioning circuits to provide an improved eye opening for reduced error rate.

These voltage decision levels are then used by three high-speed comparators  
2506-2510, which are followed by combinational logic 2512 to properly decode the  
levels back to the encoded data streams. The three comparators 2506-2510 and  
combinational logic 2512 are closely related to a traditional flash ADC with the  
30 exception of optimal threshold control (as per present invention) and decoding  
methods more amenable to communication systems than binary. The receiver  
converts the multi-level input into properly decoded data streams. It should be  
obvious to one skilled in the art that this circuit can be expanded to n-level  
transmissions by incorporating n-1 high-speed comparators, a more complex decoding  
35 logic, and a higher resolution low-speed ADC for statistic signal sampling.

One skilled in the art will understand that various combinational logic circuits  
can be designed to perform the decoding function block 2712. As illustrated by Table

5     5, adjacent levels output by an ADC effect a change of only one bit in the decoded four-bit words. These types of decoding techniques are well known to those skilled in the arts. A discussion of these techniques is given in "Digital and Analog Communications" by Gibson, published by Macmillan Publishing Company in 1993.

10    Although the present invention has been described in connection with various exemplary embodiments, those of ordinary skill in the art will understand that many modifications can be made thereto within the scope of the claims that follow. Accordingly, it is not intended that the scope of the invention in any way be limited by the above description, but instead be determined entirely by reference to the claims that follow.

15

## CLAIMS

What is claimed is:

1. A method for increasing the channel data rate throughput in an optical fiber communication system while minimizing a bit error rate, the  
10 method comprising the steps of:

receiving a digital input signal, comprising a series of input pulses, each input pulse having one of two pulse levels;

creating a digital input word having  $n$  bits from the digital input signal;

15 converting each digital input word to a corresponding output symbol representing one of  $2^n$  distinct values;

generating an output signal comprising a series of output symbols; and

modifying a first output symbol, according to a signal property of a preceding output symbol and a signal property of a succeeding output symbol.

20 2. The method of Claim 1, wherein the step of modifying the first output symbol comprises accessing a look-up table to determine an appropriate modification of a signal property of the first output symbol.

25 3. The method of Claim 1, wherein the step of modifying the first output symbol is performed by a precompensation circuit.

4. The method of Claim 1, wherein the digital input signal is received from  $n$  separate channels, the output signal having  $n$  times higher data rate than that of one of the  $n$  separate channels.

5. The method of Claim 1, wherein the digital input signal is received from a single channel.

5        6.     The method of Claim 1, wherein the spectral occupancy of the  
optical signal is minimized.

10      7.     The method of Claim 1, wherein the signal property of the  
preceding output symbol is a first amplitude and the signal property of the  
succeeding output symbol is a second amplitude and further comprising the  
step of interrogating the output signal to determine an amplitude of the first  
output symbol.

15      8.     The method of Claim 7, further comprising the step of  
interrogating the output signal to determine the amplitude of the preceding  
output symbol.

20      9.     The method of Claim 7, further comprising the step of  
interrogating the output signal to determine the amplitude of the succeeding  
output symbol.

10.     The method of Claim 7, wherein the first output symbol, is  
delayed to determine the amplitude of the succeeding output symbol.

25      11.    The method of Claim 10, wherein a transmission line is used to  
delay the first output symbol for a first delay time.

30      12.    The method of Claim 10, wherein a digital register is used to  
store the first output symbol, thereby delaying the first output symbol for a  
first delay time.

13.     The method of Claim 7, wherein the preceding output symbol,  
is delayed to determine the amplitude of the first output symbol.

5

14. The method of Claim 13, wherein a transmission line is used to delay the preceding output symbol for a second delay time.

15. The method of Claim 13, wherein a digital register is used to store the first output symbol, thereby delaying the first output symbol for a first delay time.

16. The method of Claim 1, wherein the step of modifying the first output symbol comprises modifying an amplitude of the first output symbol.

15

17. The method of Claim 16, wherein the step of modifying the amplitude of the first output symbol comprises modifying the amplitude of the first output symbol based on the amplitude of the first output symbol.

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18. The method of Claim 16, wherein the step of modifying the amplitude of the first output symbol comprises modifying the amplitude of the first output symbol based on the amplitude of the preceding output symbol.

25

19. The method of Claim 16, wherein the step of modifying the amplitude of the first output symbol comprises modifying the amplitude of the first output symbol based on the amplitude of the succeeding output symbol.

30

20. The method of Claim 16, wherein the step of modifying the amplitude of the first output symbol comprises modifying the amplitude of the first output symbol based on the phase of the first output symbol

5        21. The method of Claim 16, wherein the step of modifying the amplitude of the first output symbol comprises modifying the amplitude of the first output symbol based on the phase of the preceding output symbol.

10      22. The method of Claim 16, wherein the step of modifying the amplitude of the first output symbol comprises modifying the amplitude of the first output symbol based on the amplitude of the succeeding output symbol.

15      23. The method of Claim 1, further comprising the step of further modifying the first output symbol, according to an amplitude of a second preceding output symbol and a second succeeding output symbol.

20      24. The method of Claim 1, wherein the signal property of the preceding output symbol is a first frequency, the signal property of the succeeding output symbol is a third frequency and the signal property of the succeeding output symbol is a second frequency and further comprising the step of interrogating the output signal to determine a frequency of the first output symbol.

25      25. The method of Claim 24, wherein the step of modifying the first output symbol comprises modifying the frequency of the first output symbol.

30      26. The method of Claim 25, wherein the step of modifying the frequency of the first output symbol comprises modifying the frequency of the first output symbol based on the frequency of the preceding output symbol. The method of Claim 22, wherein the step of modifying the frequency of the first output symbol comprises modifying the frequency of the first output symbol based on the frequency of the succeeding output symbol.

5        27. The method of Claim 22, wherein the step of modifying the frequency of the first output symbol comprises modifying the frequency of the first output symbol based on the frequency of the first output symbol.

10      28. The method of Claim 1, wherein the signal property of the preceding output symbol is a first phase and the signal property of the succeeding output symbol is a second phase and further comprising the step of interrogating the output signal to determine a phase of the first output symbol.

15      29. The method of Claim 28, wherein the step of modifying the first output symbol comprises modifying a phase of the first output symbol.

20      30. The method of Claim 29, wherein the step of modifying the phase of the first output symbol comprises modifying the phase of the first output symbol based on the phase of the first output symbol.

25      31. The method of Claim 29, wherein the step of modifying the phase of the first output symbol comprises modifying the phase of the first output symbol based on the phase of the succeeding output symbol.

30      32. The method of Claim 29, wherein the step of modifying the phase of the first output symbol comprises modifying the phase of the first output symbol based on the phase of the preceding output symbol.

35      33. The method of Claim 29, further comprising the step of further modifying the first output symbol, according to a phase of a second preceding output symbol and a phase of second succeeding output symbol.

5        34. The method of Claim 29, wherein the step of modifying the  
phase of the first output symbol depends upon the amplitude of the preceding  
output symbol.

10      35. The method of Claim 29, wherein the step of modifying the  
phase of the first output symbol depends upon the amplitude of the succeeding  
output symbol.

15      36. The method of Claim 29, wherein the step of modifying the  
phase of the first output symbol depends upon the amplitude of the first output  
symbol.

5        37. A method for increasing the channel data rate throughput in an optical fiber communication system while minimizing a bit error rate, the method comprising the steps of:

receiving a digital input signal, comprising a series of input pulses, each input pulse having one of two pulse levels;

10        creating a digital input word having  $n$  bits from the digital input signal; converting the digital input word to an error resistant digital input word;

converting each error resistant digital input word to a corresponding error resistant output symbol having one of  $2^n$  distinct values;

15        generating an output signal comprising a series of error resistant output symbols; and

transmitting each error resistant output symbol to a receiver over a fiber optic link.

38. The method of Claim 37, wherein the digital input signal is received from  $n$  separate channels, the output signal having  $n$  times higher data rate than that of one of the  $n$  separate channels.

39. The method of Claim 37, wherein the digital input signal is received from a single channel.

25

40. The method of Claim 37, wherein the error resistant output symbol is convolutionally coded.

41. The method of Claim 37, wherein the error resistant output symbol is encoded with block coding.

42. The method of Claim 37, wherein the error resistant output symbol is encoded with trellis coding.

5

43. The method of Claim 37, wherein the error resistant code is a Gray code.

10 44. The method of Claim 43, wherein the Gray code is characterized by having adjacent words that are differentiated from each other by a change in only one bit.

15 45. The method of Claim 37, wherein the error resistant code is a Q-Gray code.

46. The method of Claim 45, wherein the Q-Gray code is characterized by having adjacent words that are differentiated from each other by a change in only one bit.

20 47. A method for increasing the channel data rate throughput in an optical fiber communication system while minimizing a bit error rate, the method comprising the steps of:

receiving a digital input word having  $n$  bits;

25 converting the digital input word to an error resistant digital input word;

converting each error resistant digital input word to a corresponding error resistant output symbol representing one of  $2^n$  distinct values; and

transmitting each error resistant output symbol to a receiver over a fiber optic link.

5        48. A method for increasing the channel data rate throughput in an optical fiber communication system, the method comprising the steps of:

receiving a digital input signal, comprising a series of input pulses, each input pulse having one of two pulse levels;

creating a digital input word having  $n$  bits from the digital input signal;

10              converting each digital input word to a corresponding output symbol having one of  $2^n$  distinct values;

generating an output signal comprising a series of output symbols;

15              adding a signal dependent bias to the output signal so that a linear response is generated in the optical source; and

using the optical source to transmit the output signal.

49. The method of Claim 48, wherein the digital input signal is received from  $n$  separate channels, the output signal having  $n$  times higher data rate than that of one of the  $n$  separate channels.

50. The method of Claim 48, wherein the digital input signal is received from a single channel.

25        51. The method of Claim 48, wherein error correction coding is applied to the input data.

52. The method of Claim 48, wherein a drive current controls the optical source.

30

53. The method of Claim 48, wherein the step of adding a signal dependent bias comprises changing the drive current associated with the output signal by an error current.

5

54. The method of Claim 52, wherein the drive current controls a laser diode.

55. The method of Claim 54, wherein a nonlinear element is used  
10 to shunt an error current from the drive current.

56. The method of Claim 55, wherein the laser diode is a nonlinear optical modulator device.

15 57. The method of Claim 48, wherein a drive voltage controls the optical source.

58. The method of Claim 57, wherein a series resistor is used to convert a nonlinear shunt current into a nonlinear voltage drop to reduce the  
20 drive voltage.

59. The method of Claim 57, wherein the step of adding a signal dependent bias comprises adjusting the drive voltage associated with the output signal by an error voltage.

25

60. The method of Claim 52, wherein the drive controls a Mach-Zehnder modulator.

30 61. The method of Claim 60, wherein a series resistor is used to convert a nonlinear shunt current into a nonlinear voltage drop to reduce the drive voltage.

5        62. An optical transmitter for generating an optical fiber communication signal for transmission over an optical fiber while minimizing a bit error rate, the optical transmitter comprising:

10      a symbolizer for receiving an input data signal comprising a series of pulses, each pulse having one of two distinct pulse levels, wherein the symbolizer is operative to convert  $n$  pulses from the input data signal into an error resistant  $n$ -bit output word, and further operative to generate an output symbol representing one of  $2^n$  distinct values; and

15      an optical source for transmitting an output signal comprising at least one error resistant output symbol over the optical fiber, each error resistant output symbol corresponding to one of  $2^n$  optical source intensity levels.

63. The optical transmitter of Claim 61, wherein the input data signal is received from  $n$  separate channels, wherein the output signal comprises  $n$ -times higher data rate than the  $n$  separate channels.

20

64. The optical transmitter of Claim 61, wherein the input data signal is received from a single channel.

25      65. The optical transmitter of Claim 61, wherein the error resistant output symbol is convolutionally coded.

66. The optical transmitter of Claim 61, wherein the error resistant output symbol is encoded with trellis coding.

30      67. The optical transmitter of Claim 61, wherein the error resistant output symbol is encoded with block coding.

5        68.      The optical transmitter of Claim 61, wherein the error resistant  
code is a Gray code.

10       69.      The optical transmitter of Claim 68, wherein the Gray code is  
characterized by having adjacent words that are differentiated from each other  
by a change in only one bit.

15       70.      The optical transmitter of Claim 61, wherein the error resistant  
code is a Q-Gray code.

15       71.      The optical transmitter of Claim 70, wherein the Q-Gray code  
is characterized by having adjacent words that are differentiated from each  
other by a change in only one bit.

5. 72. A transmission link for transmitting an optical fiber communication signal for transmission over an optical fiber, the optical transmission link comprising:

10 a symbolizer for receiving an input data signal comprising a series of pulses, each pulse having one of two distinct pulse levels, wherein the symbolizer is operative to convert  $n$  pulses from the input data signal into an error resistant  $n$ -bit output word, and further operative to generate an output symbol representing one of  $2^n$  distinct values; and

15 an optical source for transmitting an output signal comprising a series of the optical symbols over the optical fiber, each optical symbol having one of  $2^n$  intensity levels; and

wherein the symbolizer is further operative to modify a signal property of each optical symbol, according to a signal property of a preceding optical symbol and a signal property of a succeeding optical symbol.

20 73. The transmission link of Claim 71, wherein the input data signal is received from  $n$  separate channels, wherein the output signal comprises  $n$ -times higher data rate than the  $n$  separate channels.

25 74. The transmission link of Claim 71, wherein the digital input signal is received from a single channel.

75. The transmission link of Claim 71, wherein the symbolizer further comprises a predistortion circuit.

30 76. The transmission link of Claim 74, wherein the predistortion circuit is further operative to interrogate the output signal to determine the signal property of the first output symbol.

5        77. The transmission link of Claim 74, wherein the predistortion circuit is further operative to interrogate the output signal to determine the signal property of the preceding output symbol.

10      78. The transmission link of Claim 74, wherein the predistortion circuit is further operative to interrogate the output signal to determine the signal property of the succeeding output symbol.

15      79. The method of Claim 74, wherein the predistortion circuit performs the function of accessing a look-up table to determine an appropriate modification of the transmitted optical symbol.

20      80. The transmission link of Claim 74, wherein the signal property of the first output symbol is an amplitude of the first output signal and the predistortion circuit is further operative to modify the first output symbol by modifying the amplitude of the first output symbol.

81. The transmission link of Claim 80, wherein the predistortion circuit is further operative to modify the amplitude of the first output symbol based on the amplitude of the first output symbol.

25

82. The transmission link of Claim 80, wherein the predistortion circuit is further operative to modify the amplitude of the first output symbol based on the amplitude of the succeeding output symbol.

30

83. The transmission link of Claim 80, wherein the predistortion circuit is further operative to modify the amplitude of the first output symbol based on the amplitude of the preceding output symbol.

5. 84. The transmission link of Claim 74, wherein the signal property of the first output symbol is a phase of the first output signal and the predistortion circuit is further operative to modify the first output symbol by modifying the phase of the first output symbol.

10. 85. The transmission link of Claim 84, wherein the predistortion circuit is further operative to modify the phase of the first output symbol based on the phase of the first output symbol.

15. 86. The transmission link of Claim 84, wherein the predistortion circuit is further operative to modify the phase of the first output symbol based on the phase of the succeeding output symbol.

20. 87. The transmission link of Claim 84, wherein the predistortion circuit is further operative to modify the phase of the first output symbol based on the phase of the preceding output symbol.

5        88.      The transmission link of Claim 74, wherein the signal property  
of the first output symbol is a frequency of the first output signal and the  
predistortion circuit is further operative to modify the first output symbol by  
modifying the frequency of the first output symbol.

10       89.      The transmission link of Claim 88, wherein the predistortion  
circuit is further operative to modify the frequency of the first output symbol  
based on the frequency of the first output symbol.

15       90.      The transmission link of Claim 88, wherein the predistortion  
circuit is further operative to modify the frequency of the first output symbol  
based on the frequency of the preceding output symbol.

20       91.      The transmission link of Claim 88, wherein the predistortion  
circuit is further operative to modify the frequency of the first output symbol  
based on the frequency of the succeeding output symbol.

92.      The transmission link of Claim 71, further comprising a  
desymbolizer comprising a photodetector, a post-compensation circuit, and a  
decoder.

25

93.      The transmission link of Claim 92, wherein the desymbolizer is  
associated with a receiver functionally connected to the optical fiber, and  
wherein the desymbolizer is operative to decode the output signal into  $n$  output  
streams, each output stream having a data rate of  $1/n$  of the output signal data  
rate.

5. 94. An optical transmitter for generating an optical fiber communication signal for transmission over an optical fiber, the optical transmitter comprising:

10 a symbolizer for receiving an input data signal comprising a series of pulses, each pulse having one of two distinct pulse levels, wherein the symbolizer is operative to convert  $n$  pulses from the input data signal into an error resistant  $n$ -bit output word, and further operative to generate an output symbol representing one of  $2^n$  distinct values; and

15 an optical source for transmitting an output signal comprising at least one optical symbol over the optical fiber, each optical symbol represented by one of  $2^n$  optical intensity levels; and

wherein the symbolizer further comprises a linearizer circuit operative to introduce a corrective offset into the output signal to counteract a nonlinear response associated with the optical source.

20 95. The optical transmitter of Claim 94, wherein the input data signal is received from  $n$  separate channels, wherein the output signal comprises  $n$ -times higher data rate than the  $n$  separate channels.

96. The optical transmitter of Claim 94, wherein the input data  
25 signal is received from a single channel.

97. The optical transmitter of Claim 94, wherein a drive current controls the optical source.

30 98. The optical transmitter of Claim 94, wherein the linearizer circuit is further operative to reduce the drive current associated with the output signal by an error current.

5        99. The optical transmitter of Claim 94, wherein the linearizer circuit comprises a nonlinear element operative to shunt the error current from the drive current.

10      100. The optical transmitter of Claim 94, wherein the corrective offset comprises a reduction in the drive voltage associated with the output signal by an error voltage.

15      101. A method for increasing the data throughput of an existing optical fiber communications system without replacing an optical fiber plant associated with the existing optical fiber communications system, the method comprising the steps of:

20      replacing an existing transmitter with an upgrade transmitter having a symbolizer for receiving an input data signal comprising a series of pulses, each pulse having one of two distinct pulse levels, wherein the symbolizer is operative to convert  $n$  pulses from the input data signal into an error resistant  $n$ -bit output word, and further operative to generate an output symbol representing one of  $2^n$  distinct values; and, the output symbol representing the  $n$ -bit output word; and

25      replacing an existing receiver with an upgrade receiver having a desymbolizer operative to receive and decode an output signal generated by the upgrade transmitter, the output signal comprising a series of output symbols.

30      102. The method claim of 101, wherein the symbolizer is further operative to convert each output symbol to an  $n$ -bit error protected symbol using error protection coding, and wherein the transmitted output signal comprises  $n$ -times higher data rate than a data rate associated with each of the separate input data signals.

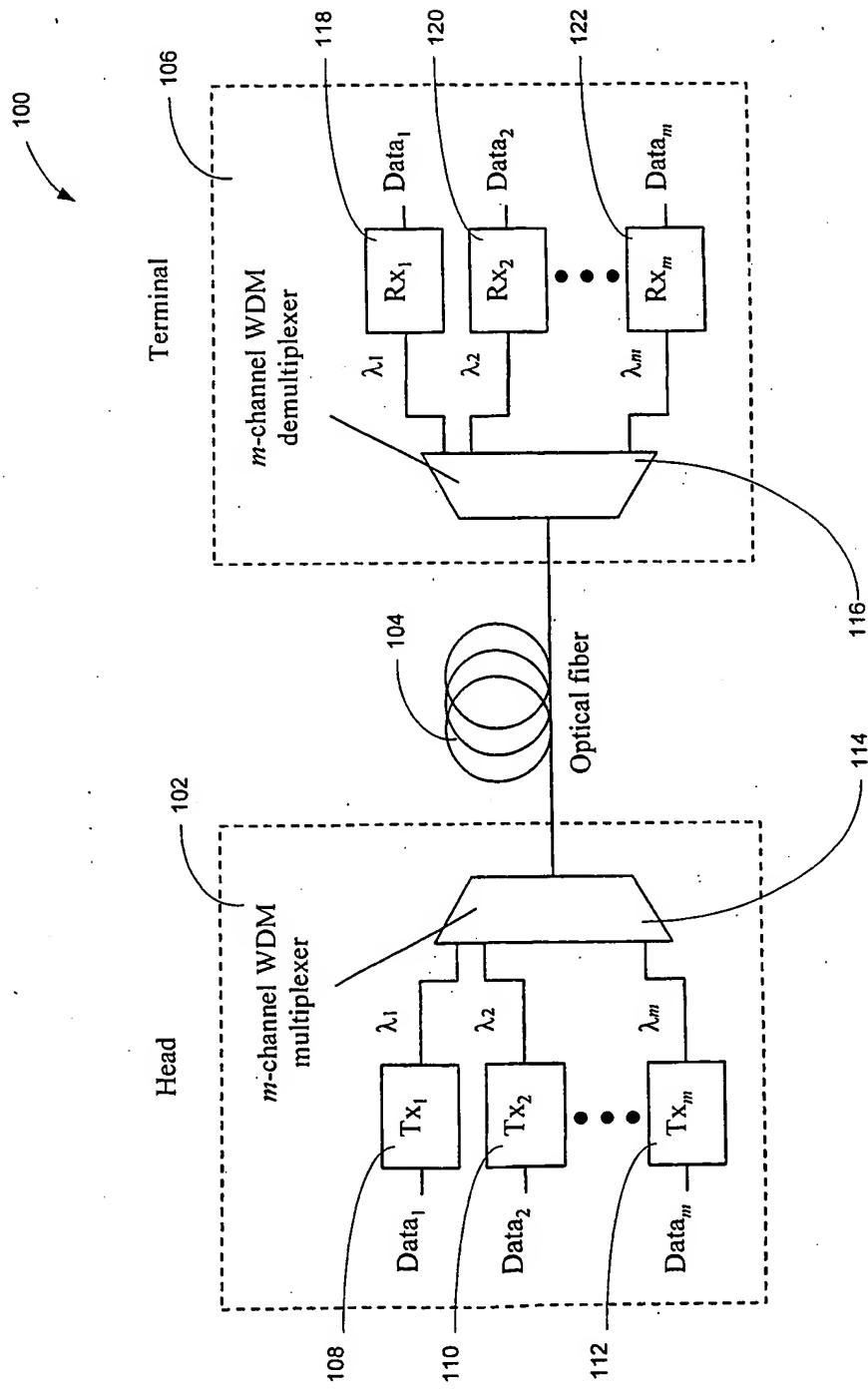
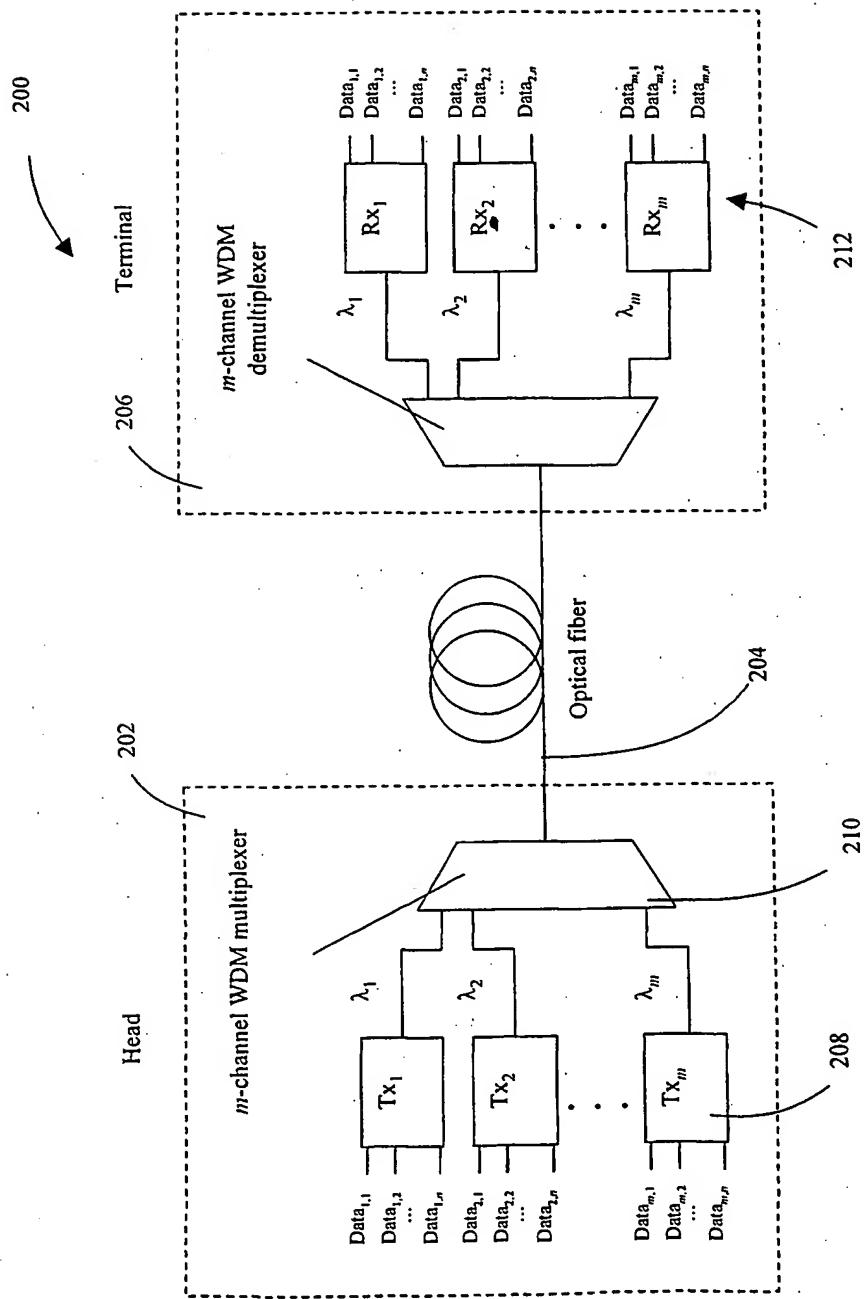


Fig. 1



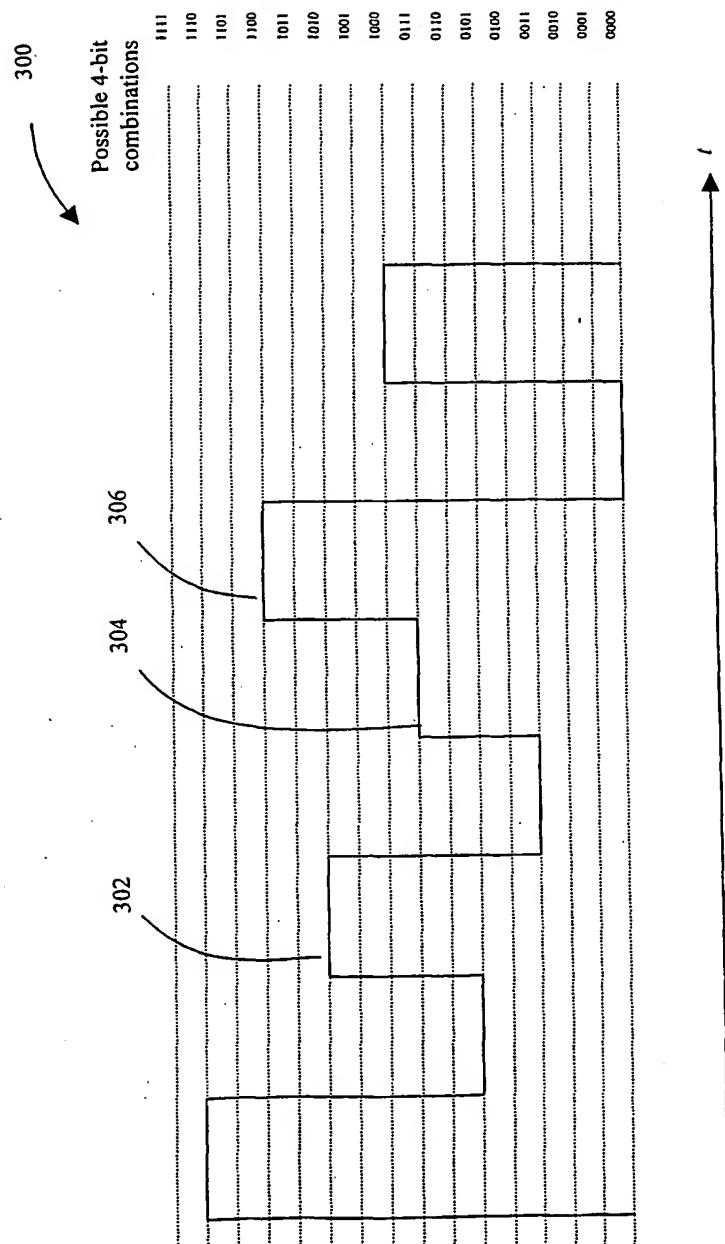


Fig. 3

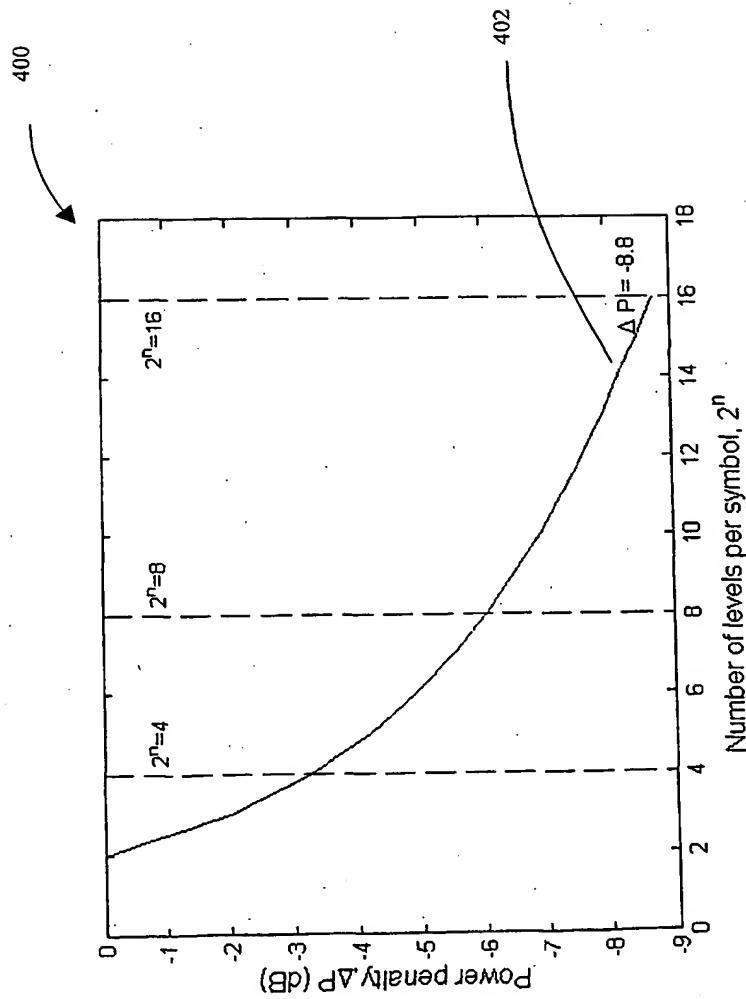


Fig. 4

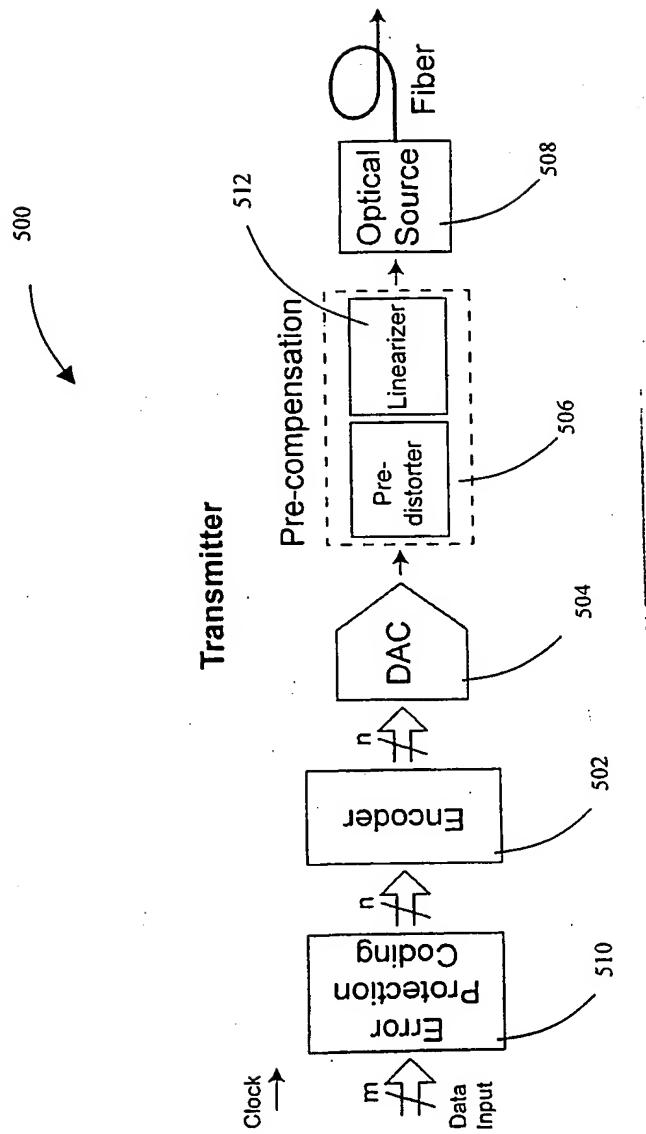


Fig. 5

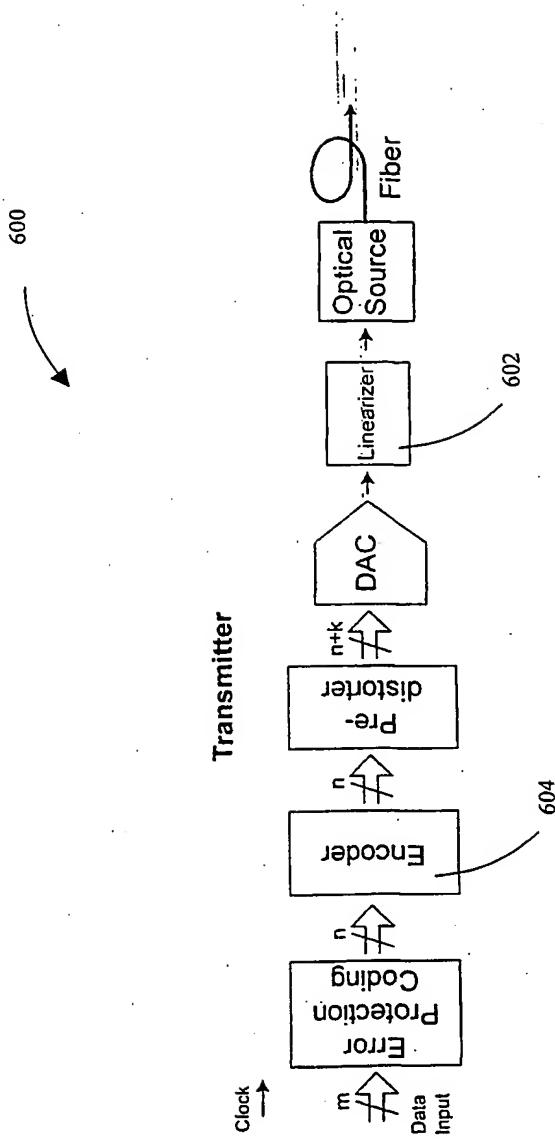


Fig. 6

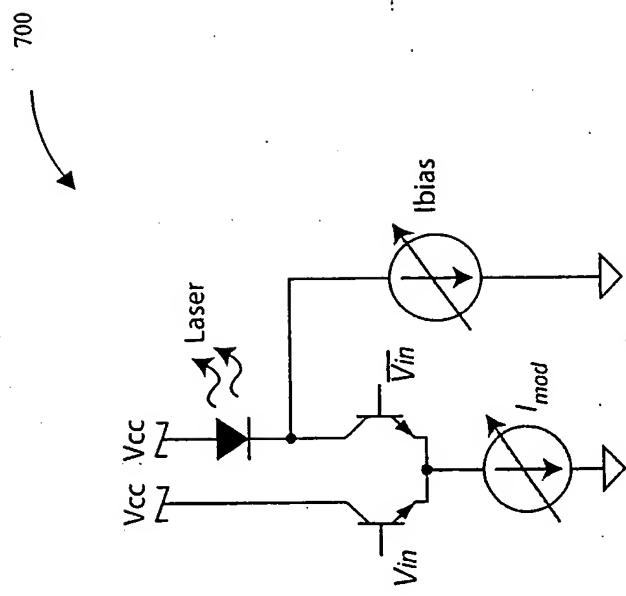
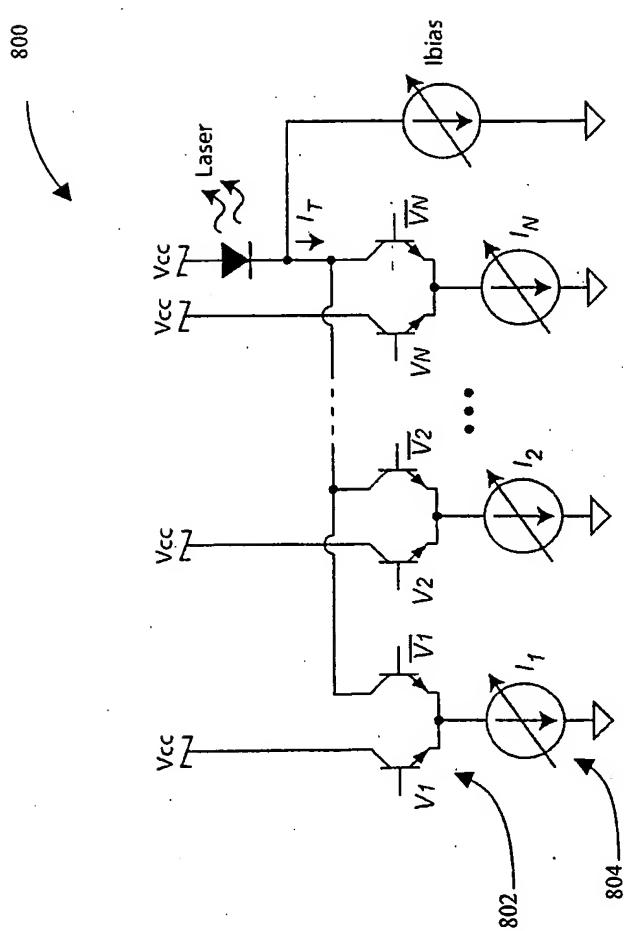
*Fig. 7*

Fig. 8



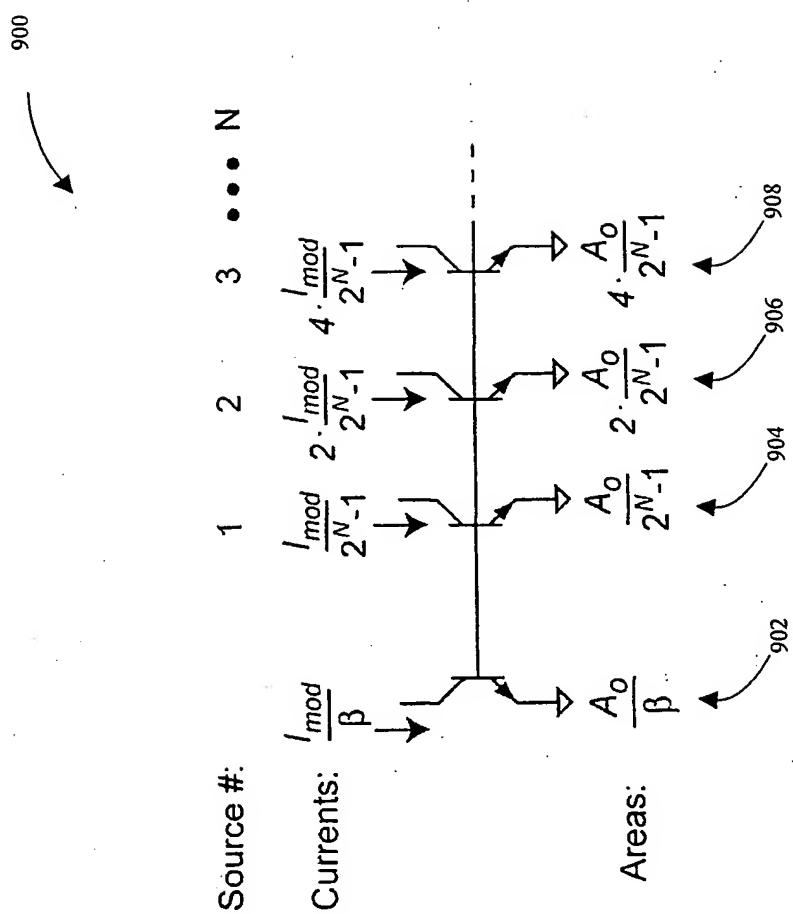


Fig. 9

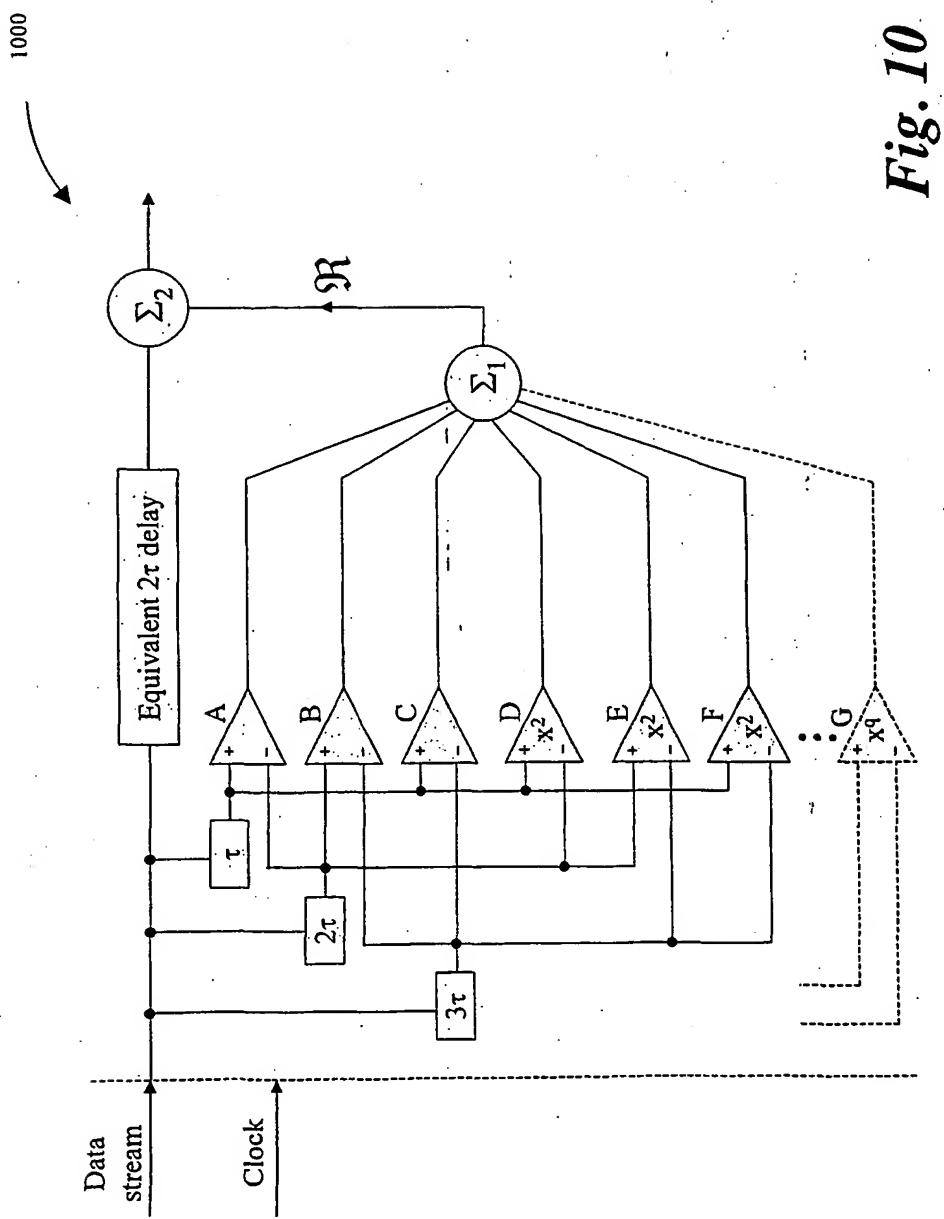
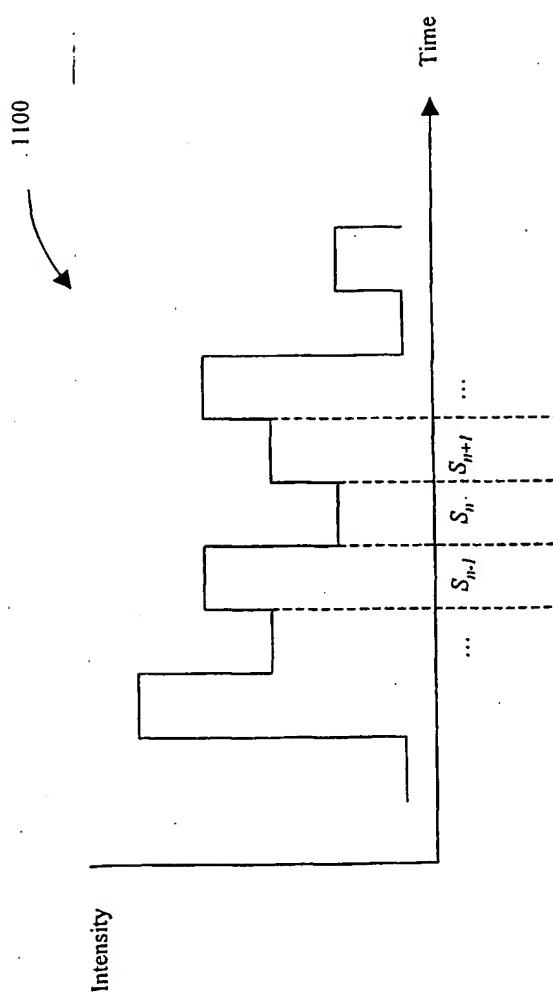
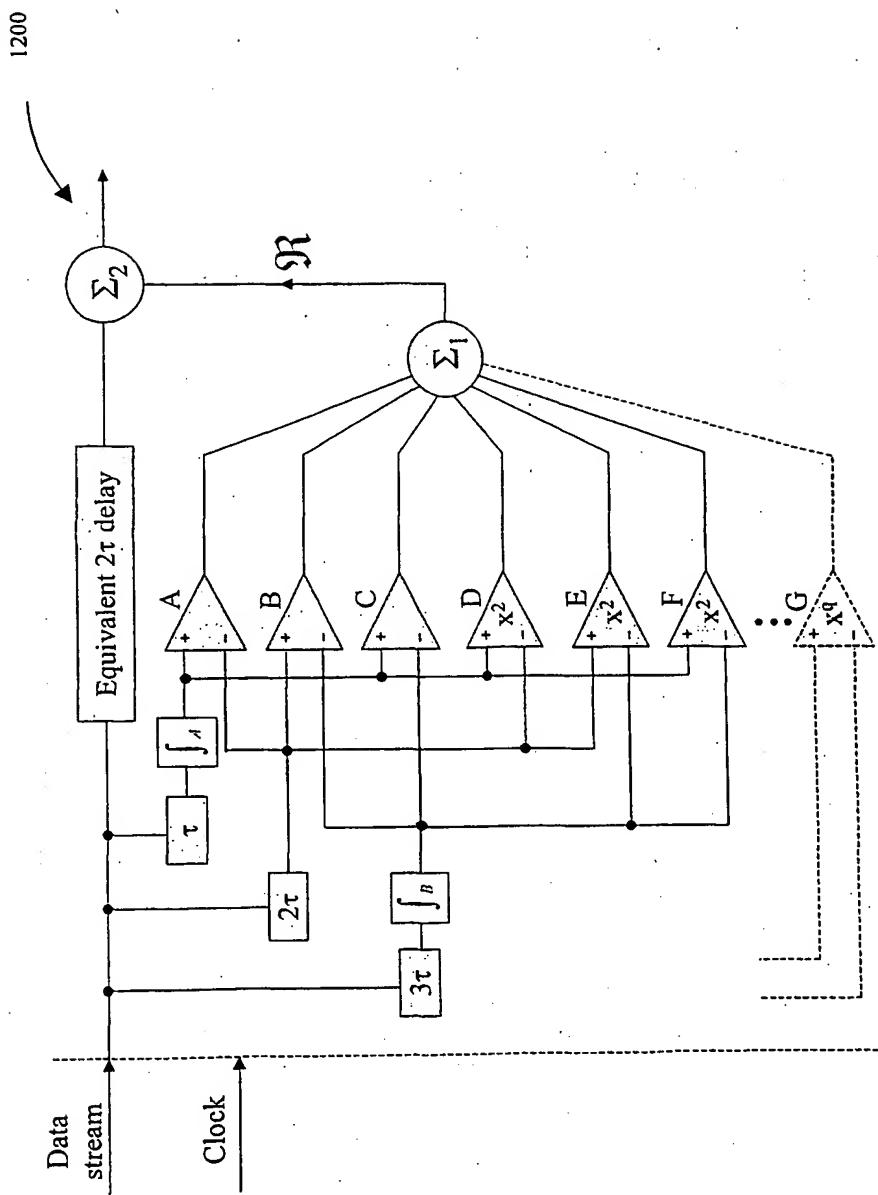


Fig. 10

*Fig. 11*

*Fig. 12*

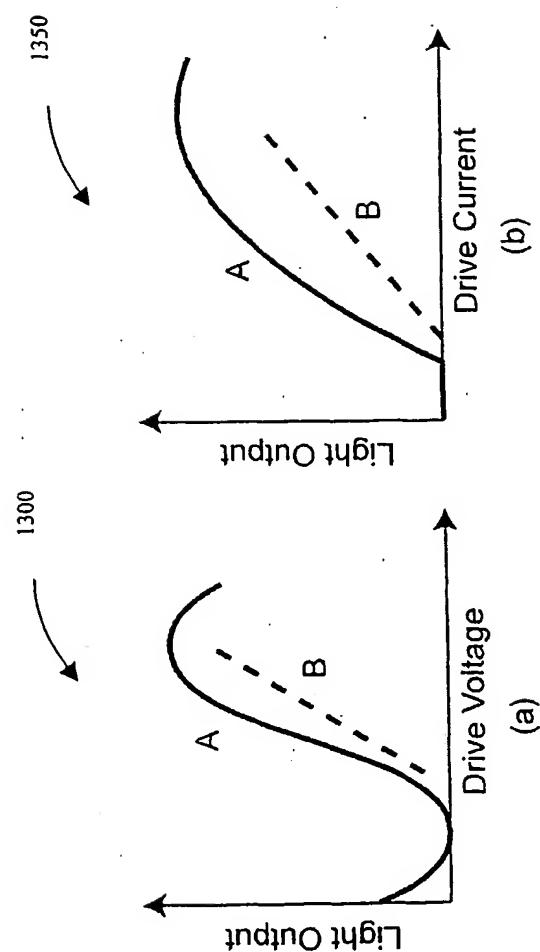


Fig. 13

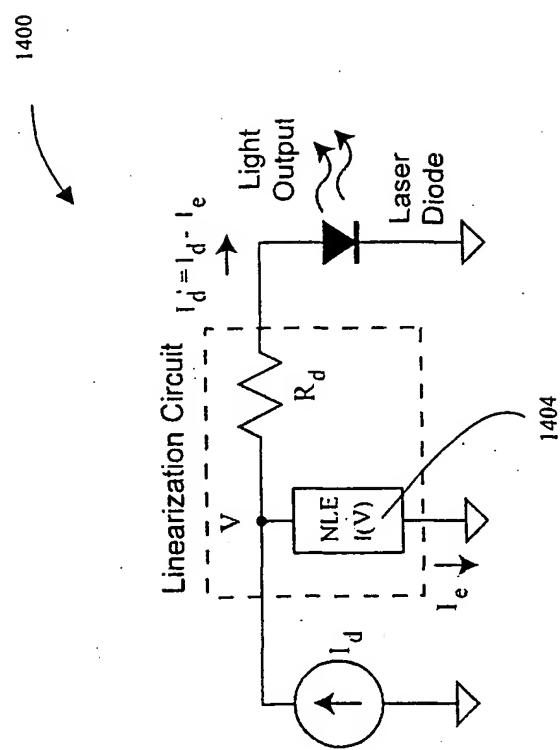


Fig. 14

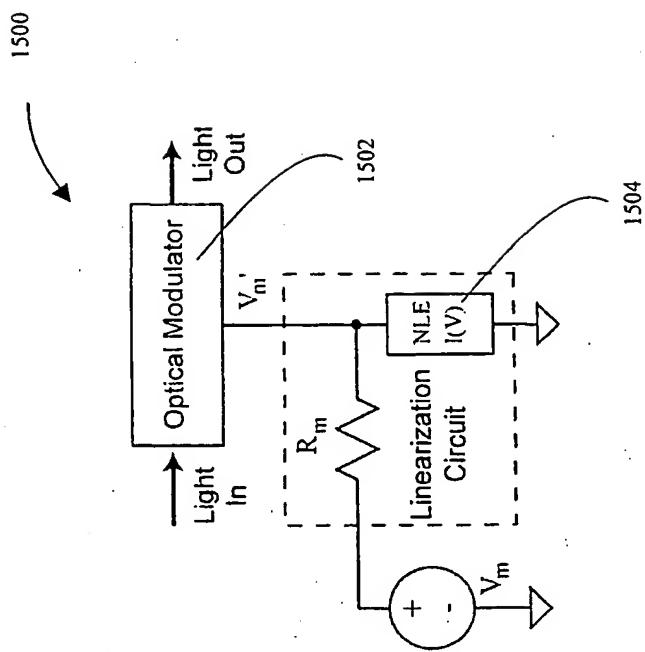
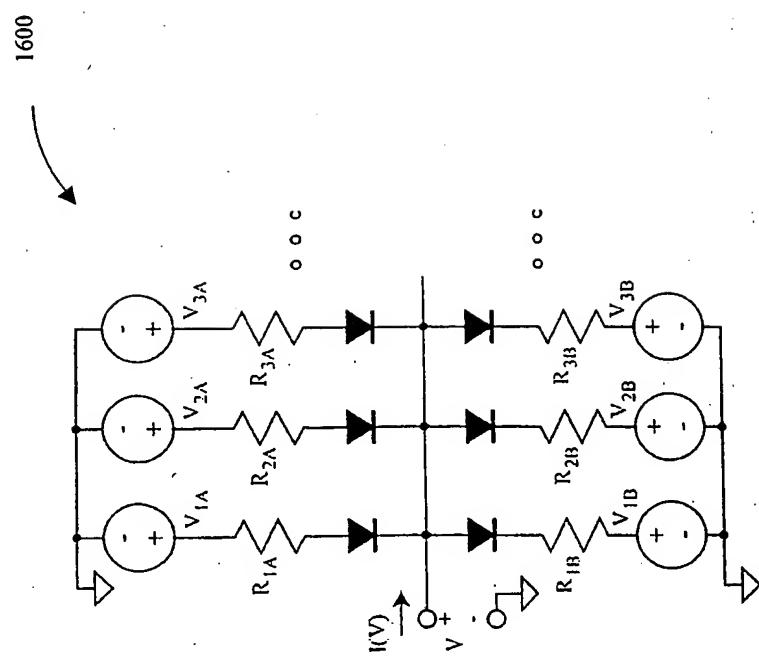
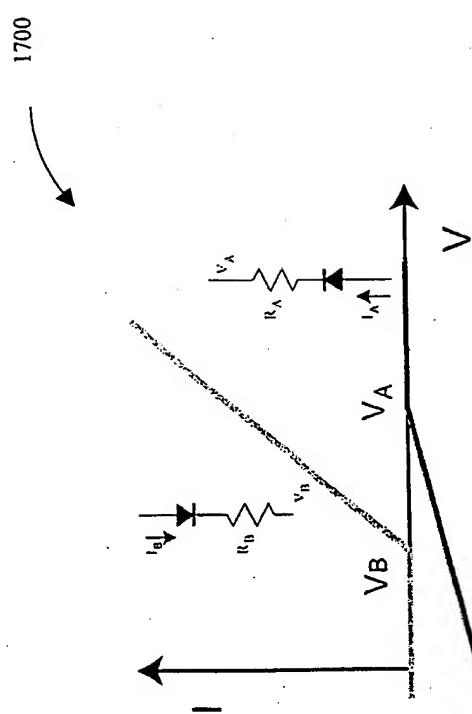
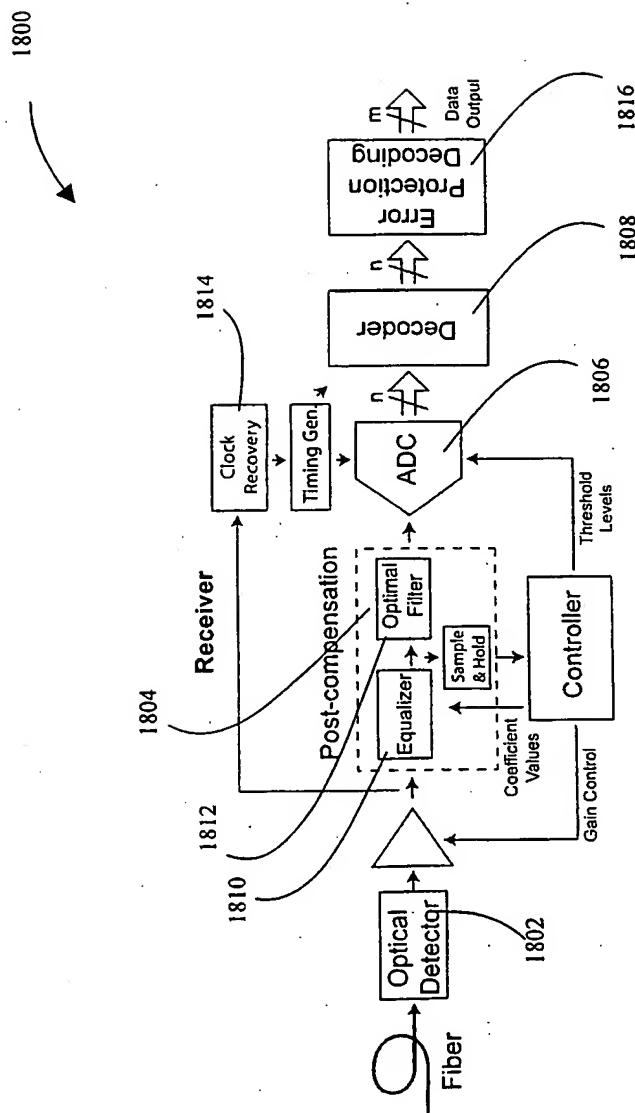
*Fig. 15*

Fig. 16



*Fig. 17*

*Fig. 18*

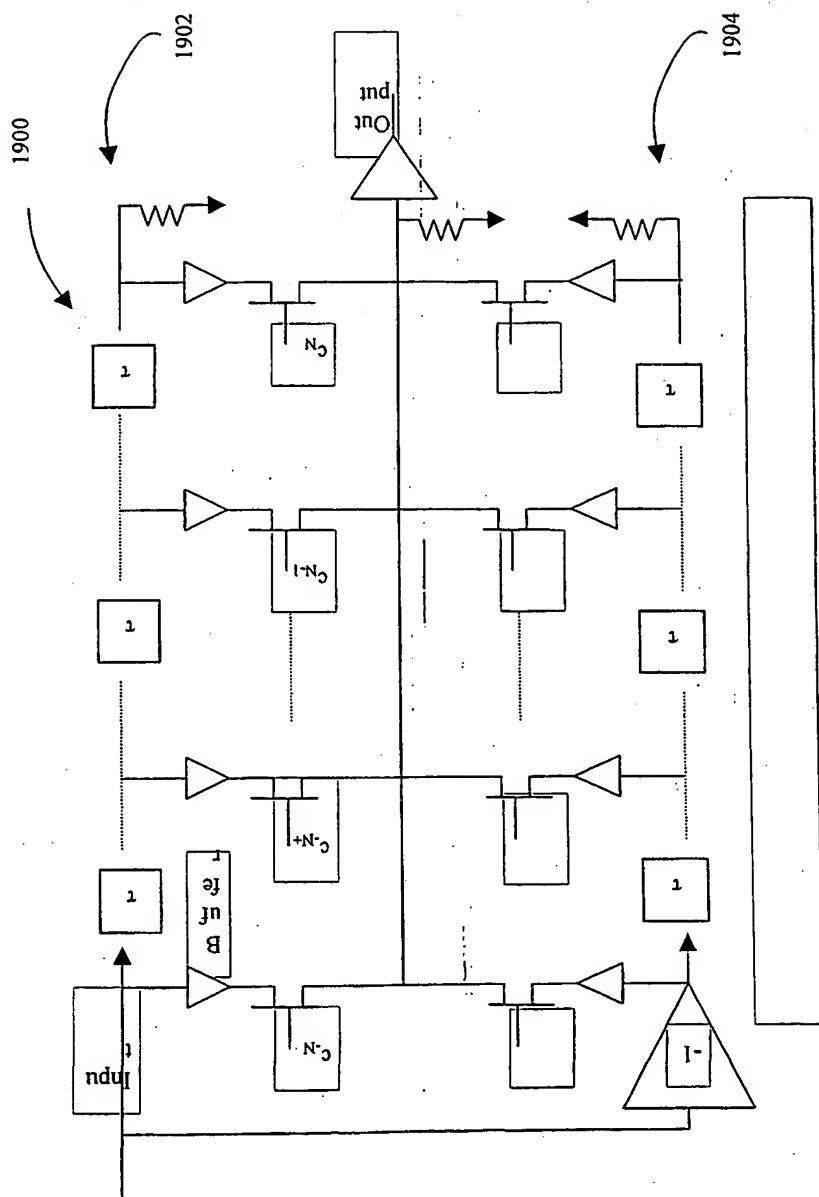
*Fig. 19*

Fig. 20

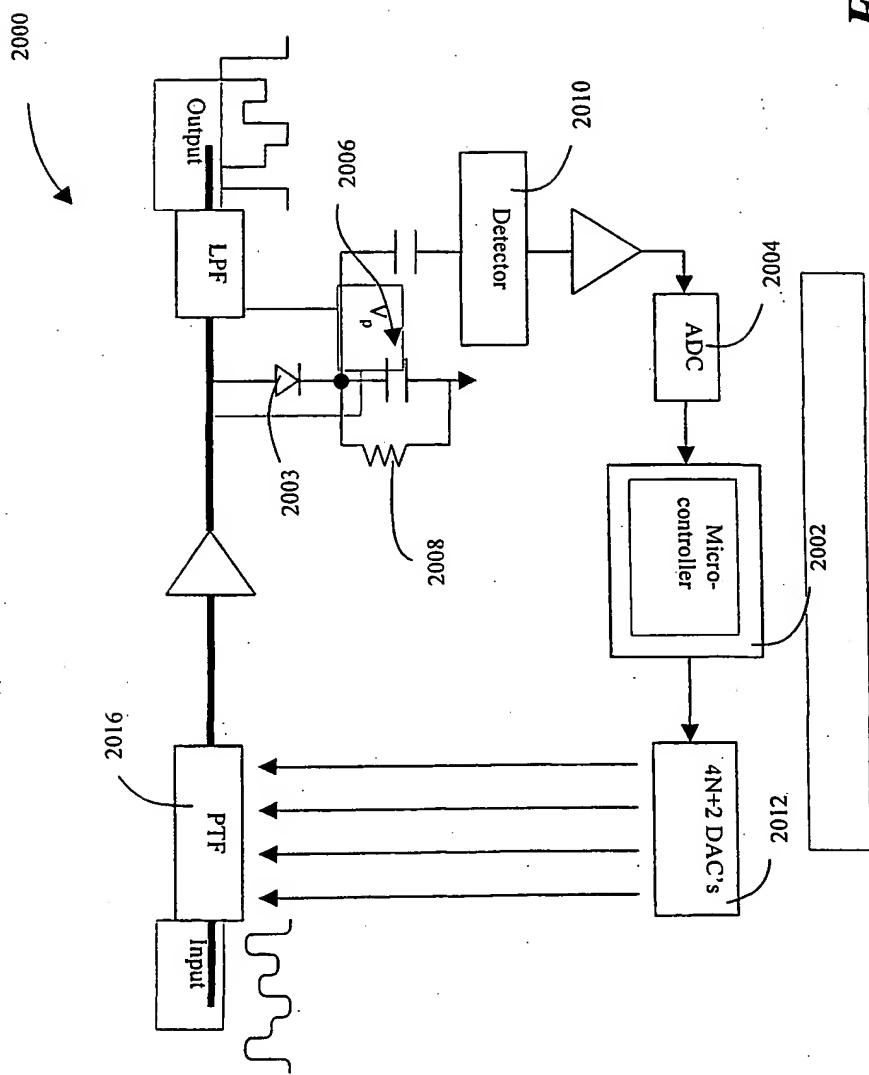
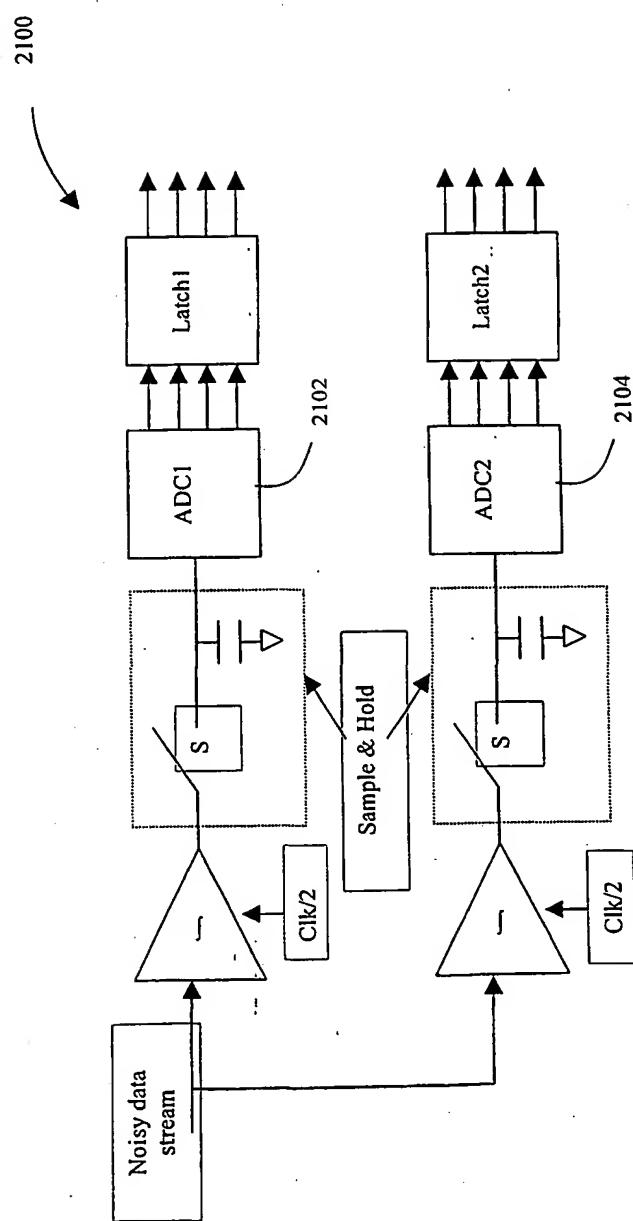


Fig. 21



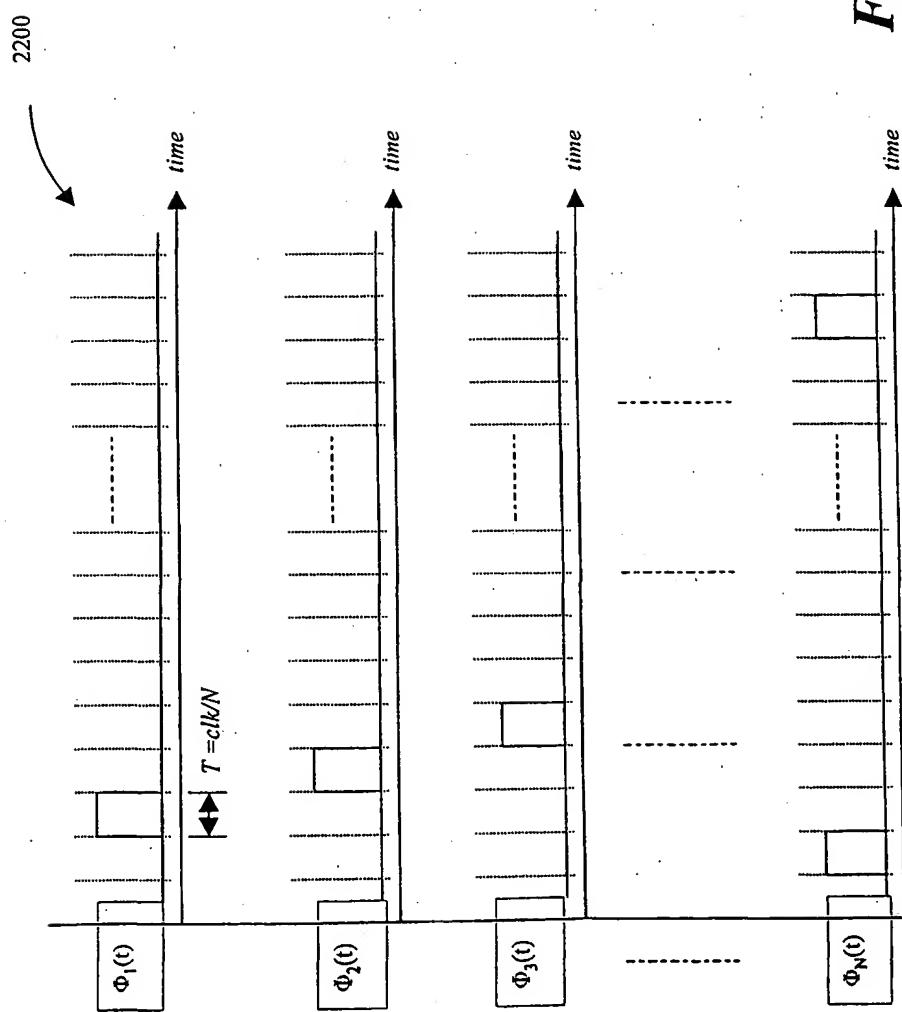


Fig. 22

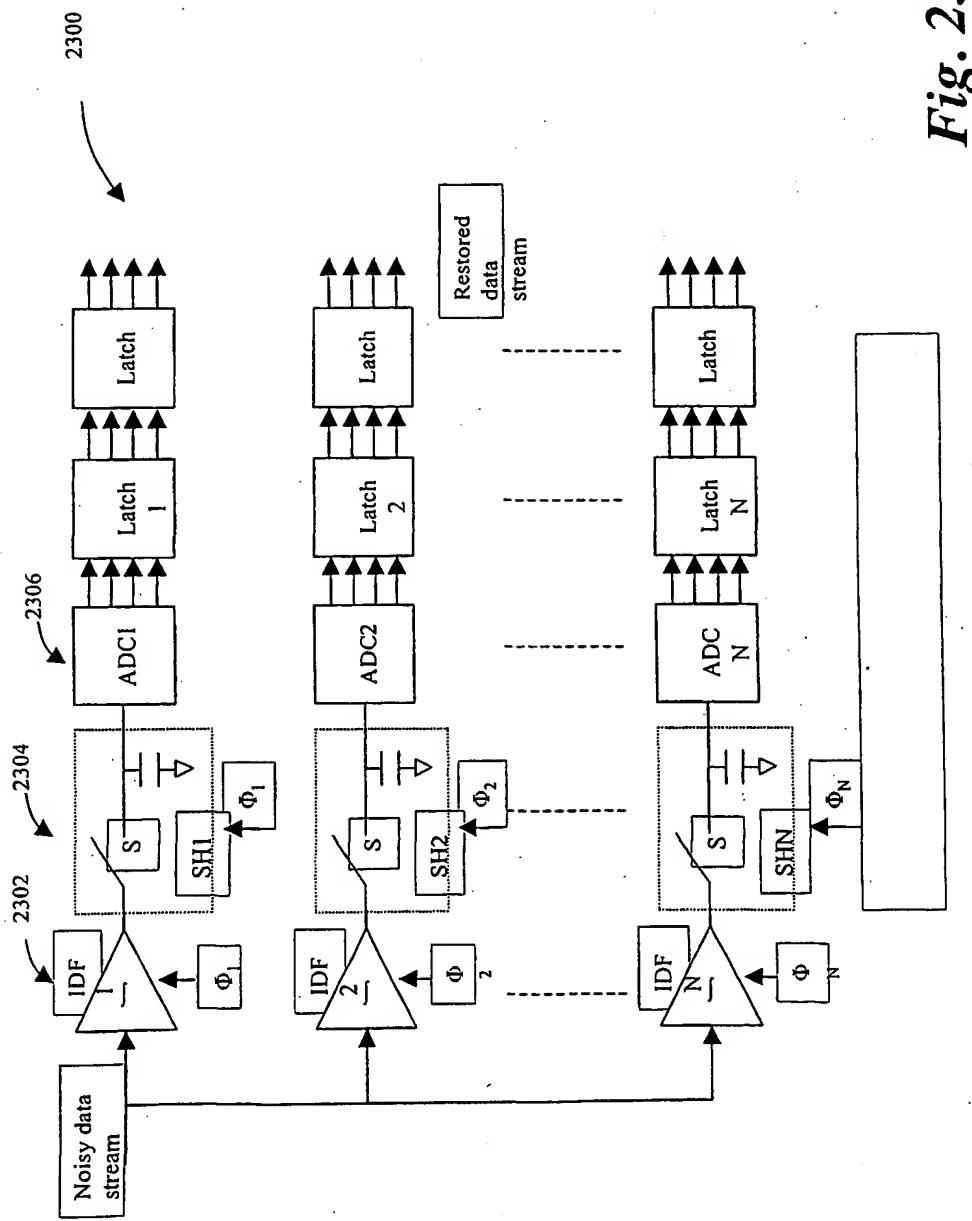
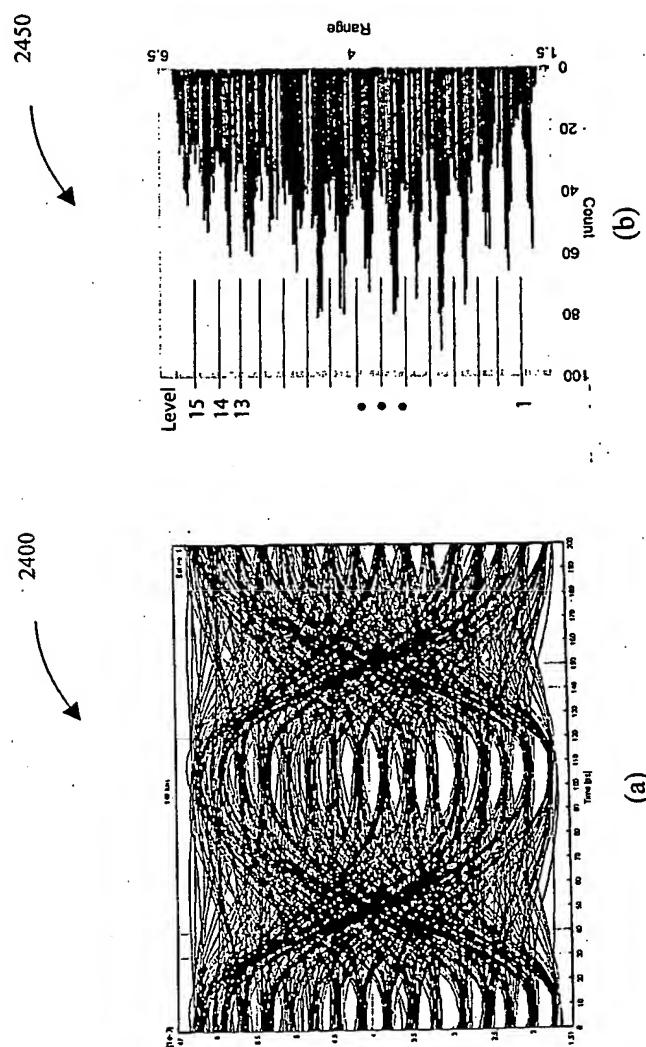


Fig. 23

*Fig. 24*

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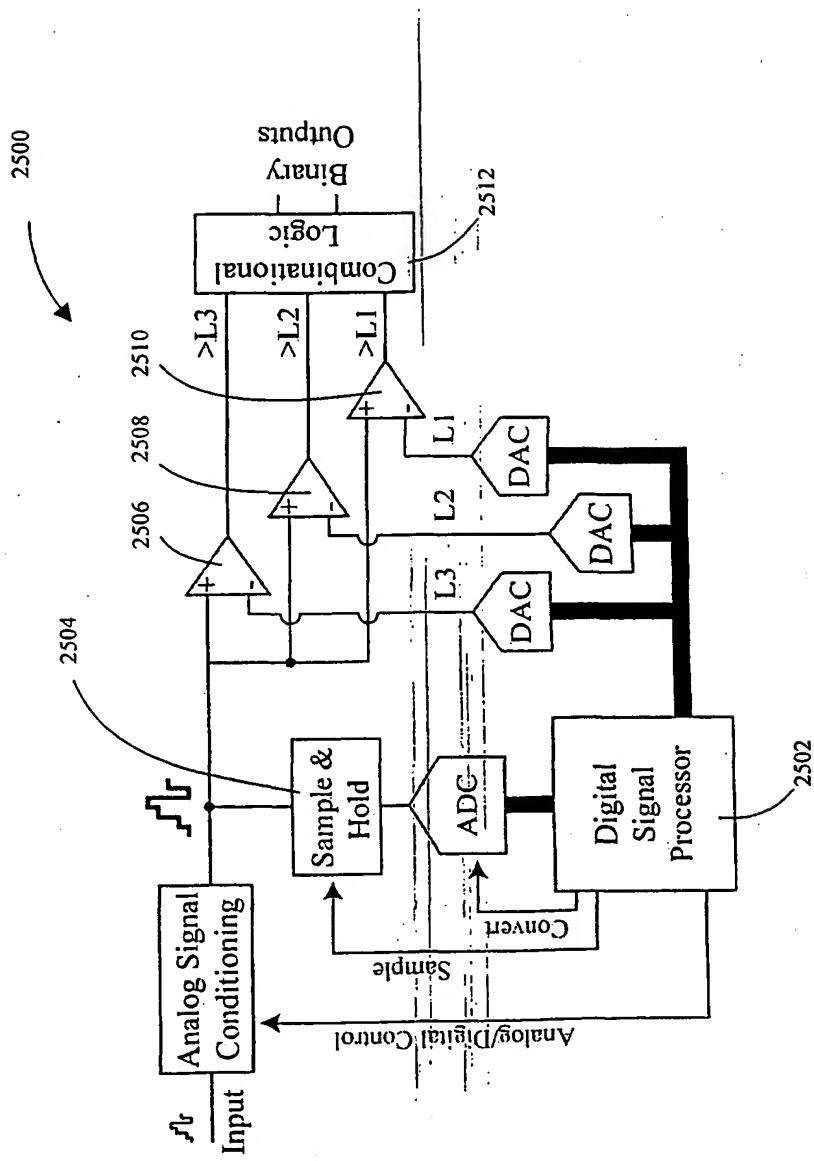


Fig. 25

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## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US01/50695

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H04L 27/18, 25/49, 5/12; H04B 10/00

US CL : 375/39, 26117, 54; 359/157, 161

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 375/39, 26117, 54; 359/157, 161

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched  
None

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST, WEST, precompensation, trellis coding, symbol mapper, digital, Gray code, optical.

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,222,103 A (GROSS) 22 January 1993, Figures 1, 3, and 4, column 1, lines 6-48, col. 3, lines 56-60, col. 4, lines 12-67, col. 5, lines 1-62.	1-102
Y	US 5,282,072 A (NAZARATHY et al) 25 January 1994, Figure 16, column 12, lines 25-67, col. 13, lines 1-57.	1-36, 48-61, and 94-100
Y	US 6,031,874 A (CHENNAKESHU et al) 29 February 2000, Figure 1, column 1, lines 5-22 and lines 55-67, col. 2, lines 1-67, col. 3, lines 1-45.	37-47, 62-93, 101, and 102
Y, P	US 6,212,654 B1 (LOU et al) 03 April 2001, Figures 1 and 2, column 4, lines 62-67, and from col. 5, line 1 to col. 7, line 3.	37-47, 62-93, 101, and 102

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 Further documents are listed in the continuation of Box C.  See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

16 JUNE 2002

Date of mailing of the international search report

12 JUL 2002

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